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THE RUTGERS STRATEGY FOR COMPOSTING: PROCESS DESIGN AND CONTROL

by

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Grant No. R806829010

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U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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16. ABSTRACT

A strategy for sludge composting was developed to counter the tendency of other composting systems to operate at high temperatures that inhibit and slow decomposition. This method, known as the Rutgers strategy, can be implemented in a static pile configuration to retain structural and operational simplicity, or in a more elaborate enclosed or reactor structure system. The method maintains a temperature ceiling that provides a high decomposition rate through on-demand removal of heat by ventilation (thermostatic control of a blower).

Compared with the approach currently in widespread use, the Rutgers strategy yields high-rate composting that decomposes four times more waste in half the time.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxics Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

The report concerns composting as a sewage sludge treatment technology. Unlike the familiar, informal, small-scale "backyard" composting of leaves, grass clippings, and other plant remains, municipal-scale composting poses significant problems in facility design and control. By following scientific and technical principles, as developed herein, the public acceptability and cost-effectiveness of such facilities can be greatly improved.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

The main determinant of composting process performance is decomposition rate. This rate is negatively affected by temperature exceeding 60°C, owing to the inactivation of the responsible microbial community. Nonetheless, composting masses typically self-heat to 80°C, at which point the rate of decomposition is low. The desired temperature ceiling providing a high rate can be maintained through on-demand ventilative heat removal (thermostatic control of a blower). This constitutes, in essence, the Rutgers strategy for composting process design and control.

This strategy, compared to the approach currently in widespread use, yields high rate composting in that approximately 4X more waste is decomposed in half the time. Although the strategy can be implemented in certain enclosed (in-vessel) configurations, the suggested unenclosed static pile configuration is advantageous in being structurally and operationally simple, and capital non-intensive.

The rational for this strategy may be expressed symbolically as follows:

$$\underline{Q}_v \cong 0.9\ \underline{m}\ (\underline{h}_{out} - \underline{h}_{in})$$

where: $\underline{Q}_v$ = heat removed through vaporization (energy/time)

0.9 = approximate proportion of total heat removed through vaporization

$\underline{m}$ = dry air mass flow (mass dry air/time)

$\underline{h}_{out}$ = enthalpy of outlet air (energy/mass dry air)

$\underline{h}_{in}$ = enthalpy of inlet air (energy/mass dry air)

The goal is to maximize $\underline{Q}_v$, because this is functionally equivalent to maximizing the rate of waste (e.g. sewage sludge) decomposition. Realistically, this can only be approached through manipulation of $\underline{m}$ (= time-variable adjustment of ventilation rate) such that the value of $\underline{h}_{out}$ corresponds to a temperature of 60°C or less. This translates to temperature feedback (thermostatic) control of a blower.

This report was submitted in fulfillment of Contract No. R806829010 by Rutgers University under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period 10/8/79 to 11/7/81, and work completed as of 11/7/81.

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Thanks are expressed to the field crew at the Camden County (New Jersey) Municipal Utilities Authority Sewage Sludge Composting Facility (Horace T. Banks, Foreman), for their cooperation in setting up the field trials.

We greatefully acknowledge Dr. Peter F. Strom for many discussions on the intricacies of composting dynamics.

SECTION 1

BACKGROUND

SLUDGE MANAGEMENT GOALS

Composting can serve as a sludge treatment technology because it advances the goals of decomposing putrescible (odor-causing) material, decreasing volume, weight, and water content, inactivating pathogenic organisms, and producing a stabilized process residue. This residue is more easily stored, transported, and disposed of than the sludge. Thus, composting is a treatment option within an overall sludge management plan.

A minimum accomplishment of composting would be to convert a sludge which is not acceptable for disposal at a sanitary landfill to a process residue of lesser amount, which is acceptable. More desirably, a use would be found for the residue. The traditional use is as a compost (organic soil amendment) in gardening and horticulture, and this might be extended to reclamation of disturbed land and the preparation of landfill cover material. A novel possibility, resulting from composting's capacity to remove water, is to use the residue as a waste-derived, low grade, solid fuel.

COST-EFFECTIVENESS AND PUBLIC ACCEPTABILITY

Even if a use is found for the process residue its monetary value will, in all likelihood, be small relative to capital and operating costs. Consequently, cost-effectiveness does not reside primarily in product sales, but rather in economical construction and operation. Thus, the facility should not be viewed, for example, as a compost factory, but rather as a sludge management center. This leads to a process, rather than a product, orientation (1).

In addition to being cost-effective, the facility must be publicly acceptable in terms of aesthetics. This requires an absence of odor nuisance, insect breeding, rodent harborage, etc.. Such nuisances often have public health overtones.

IMPORTANCE OF DECOMPOSITION RATE

Both public acceptability and cost-effectiveness hinge on the rate of decomposition. The basic preventative measure against odor production is to speed the decomposition of the putrescible organic waste. Similarly, a high rate of decomposition is consistent with low capital and operating costs. This is because a high rate results in a need for less facility time/space and structural appurtenances to achieve a given degree of stabilization, less material to be handled, stored, and transported, and improved handleability. It is necessary, therefore, to identify the operative rate-limiting factors.

OVERRIDING RATE LIMITING FACTOR: INTERACTION BETWEEN HEAT GENERATION AND TEMPERATURE

With the partial exception of pathogen inactivation (see Section 11), the aforementioned sludge management goals (decomposition of putrescible material, decreasing the volume, weight, and water content, producing a stabilized residue) may be equated with the generation of heat. This is because the heat is generated microbially through decomposition of the waste; hence, heat generation is functionally equivalent to waste treatment. In understanding the physical, chemical, and biological dynamics which govern the composting system, it is useful to focus on heat generation. In particular, the overriding determinant of system behavior is an interaction between heat generation and temperature (2-3).

Consider the behavior of a non-managed pile of organic material having the following characteristics: it is large enough to be self-insulating; the material is moist and nutritionally supportive of microbial growth; the material is sufficiently porous to allow gas exchange; the exchange suffices to prevent gross oxygen depletion in the interstitial atmosphere. Such a pile spontaneously increases in temperature because, for a period of time, the rate of microbial heat generation within the pile exceeds the rate of heat loss to the surroundings. This "self-heating" phenomenon is the basis of the composting process.

At the outset of self-heating a positive feedback loop becomes established between microbial heat generation and temperature, in that higher temperatures favor microbial growth with its associated metabolic generation of heat. When the temperature begins to exceed approximately 38°C the feedback turns negative, because higher levels are progressively unfavorable to mesophilic* growth and activity. This slows the temperature ascent and would, in the absence of subsequent events, terminate it at approximately 50°C.

The temperature ascent is renewed, however, with the initiation of thermophilic* growth, starting at approximately 45°C. This reestablishes positive feedback between heat generation and temperature. Since the thermophilic community in self-heating organic masses is most active at approximately 55°C, the feedback starts to become negative when the temperature exceeds this value. The temperature ascent again slows, typically peaking at 80°C. At this temperature, heat generation is slight.

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*Mesophile = an organism living in the temperature range around that of warm-blooded animals; thermophile = an organism living at high temperature (T.D. Brock, D.W. Smith, M.T. Madigan. Biology of Microorganisms, 4th Edition, Prentice-Hall, Inc., 1984). A competent array of both types is reliably present in organic wastes.

To realize a high rate of decomposition the system's tendency to self-limit via inhibitively high temperature must be countered. A means of doing so is to match ventilative heat removal to heat generation in reference to a 60°C ceiling, as accomplished through temperature feedback control of a blower. This development, which paved the way for the present work, was described earlier (2-7). It constitutes the approach to composting process control known as the Rutgers strategy.

CONFIGURATION AND STRATEGY: TWO LEVELS OF COMPOSTING PROCESS ORGANIZATION

Two levels of composting process organization can be recognized. Strategy lies at the conceptual level, in that it represents a plan for guiding the interacting physical, chemical, and biological events. Implementation of a strategy is through some set of physical and mechanical elements, including geometry of the composting mass, equipment for ventilation, and machinery for material handling. The elements at this level of process organization are collectively termed configuration. The distinction between strategy and configuration is basic to this investigation.

The configuration used was that of unenclosed static pile — meaning that the material was in the open, was ventilated by blower, and was not agitated mechanically during composting.

SIGNIFICANCE OF THE RUTGERS-BELTSVILLE COMPARISON

An essential feature of this report is a comparison between the Rutgers strategy and the strategy embodied in the Beltsville Static Pile Process. These represent fundamentally different approaches to the management of the composting microbial ecosystem (TABLE 1).

The Beltsville Process was developed specifically for the treatment of sewage sludge (8-11), and is in widespread use (12-13). This process is advantageous in its structural and operational simplicity, owing to the static pile configuration. Like most composting systems, however, it suffers from slow decomposition as a result of inhibitively high temperature. By employing the Rutgers strategy, however, in static pile configuration the structural and operational simplicity can be retained, while benefitting from rapid decomposition.

The difference in behavior induced by the two strategies originates in the management of ventilation. The Rutgers strategy focuses on heat removal for temperature control, whereas the Beltsville Process focuses on the maintenance of an oxygenated condition. These operational objectives are met through the respective approaches taken to blower control, sizing, and operation mode. The physical, chemical, and biological dynamics governing the composting system, however, dictate certain consequences that might not be immediately apparent. By focusing on temperature in this manner an abundance of oxygen is automatically provided, whereas by focusing on oxygen inhibitively high temperatures result. These principles pertain to composting in general, regardless of the particular type of waste being treated, the configuration employed, or the name or proprietary status of the process.

TABLE 1. FUNDAMENTALLY DIFFERENT COMPOSTING PROCESS CONTROL STRATEGIES[*]

	Process control strategy	
	Rutgers	Beltsville
Process control operational objective	Maintain 60°C temp ceiling	Maintain O_2 at 5% to 15%
Blower control	Fixed schedule initially, followed by temp feedback	Fixed schedule throughout
Blower sizing	Must meet peak demand for heat removal	Prescribed as 1/3 hp per 50 ton pile
Blower operation mode	Forced-pressure	Vacuum-induced
Consequences of strategy	System oxygenated; a high rate of heat generation[†] and vaporization; dryness may come to inhibit activity, unless prevented; good pathogen kill.	System oxygenated; temp peaks, by default, at an inhibitively high level (~80°C); a low rate of heat generation[†] and vaporization; good pathogen kill.

[*] Both strategies were implemented in unenclosed static pile configuration.

[†] Heat generation is equivalent to decomposition.

POSITION OF THE PRESENT REPORT

Most of the essential findings reported herein have already been published (1-7, 14-26) or are in an advanced stage of publication (27-30). These papers represent different facets of a coherent line of research, but are scattered. The present Report permits a more integrative treatment in a single volume, and provides an opportunity to document the data in full detail.

Finally, our basic view on composting process design and control, first enunciated in detail in 1980 (4), has received independent confirmation by at least four groups. Two of the studies were sponsored by EPA (31-33) and two were conducted in European countries (34-36).

SECTION 2

MATERIALS AND METHODS

Materials and methods generally employed in the investigation are described in the present section. Modifications and additional procedures pertaining to particular studies are described in the individual sections.

Site. Our pilot-scale composting research facility was located at the Camden County Municipal Utilities Authority sewage treatment plant at Second Avenue and Jackson Street, Camden, N.J., where the Authority routinely composted the sludge from their Jackson Street and Baldwin Run treatment plants (total 18-23 dry tonnes/day) (20-25 tons/day) by means of the Beltsville static pile process (8-11). Although sludge, woodchips, and supportive services were provided by the Authority, the investigation reported herein was independently designed and executed.

At the pilot research facility (Figure 1) a shed housed the instrumentation and control systems (Figure 2). The shed was heated and ventilated to prevent temperature extremes.

Sludge. The sludge consisted of a mixture from two sources. Approximately 90% of the material came from the Jackson Street plant, where sewage treatment consists solely of primary settling. The remainder came from Baldwin Run, where "partial digestion" was accomplished in an Imhoff tank. Thus, the experimental material was essentially raw fresh sludge.

The Jackson Street plant served a mixed residential-industrial area, where a food processing plant was the largest industrial contributor. The sludge was preconditioned with the addition of approximately 1 kg (2.2 pounds) of polymer (Allied Colloid Percal 728, a chloride based cationic polyeletrolyte) per metric tonne (1.1 ton) dry solids, followed by dewatering through a belt filter press. This generally yielded a cake of approximately 25% solids (oven dry weight expressed on a wet weight basis). Analyses of the sludge are available (37).

Woodchips. Virgin woodchips from hard and soft woods having nominal dimensions of 2.5 x 2.5 x 0.6 cm (1 x 1 x 1/4 in.) were used to form a base for the composting pile, as a bulking agent for mixing with the sludge, and to form a cover over the composting pile.

Mixture. Sludge cake (by wet weight) and woodchips (by volume) were mixed in a ratio of approximately 1 tonne sludge per 1.7 m^3 woodchips (1 ton per 2 yd^3). Mixing was done in an industrial pug mill

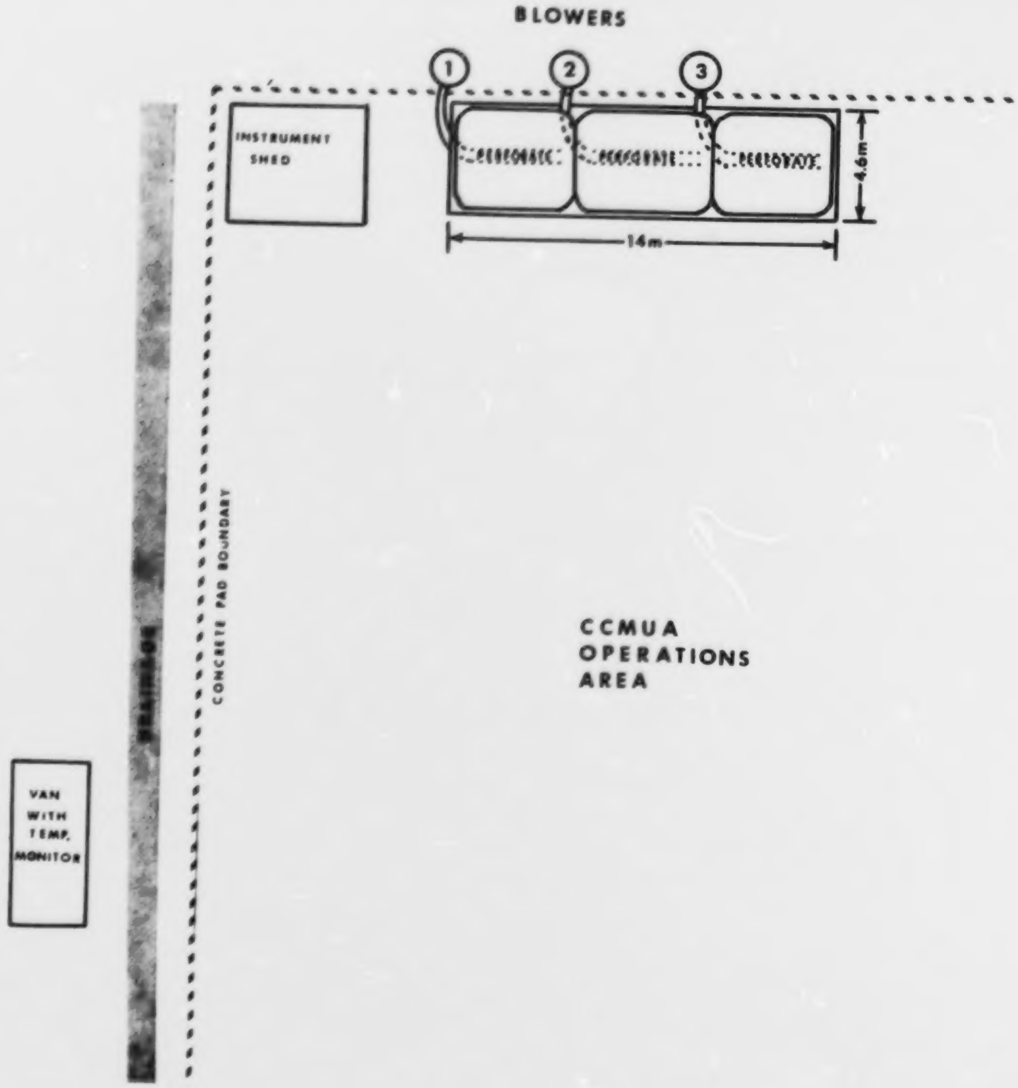

BLOWERS
1
2
3
INSTRUMENT SHED
4.6m
14m
DRAINAGE
CONCRETE PAD BOUNDARY
CCMUA OPERATIONS AREA
VAN WITH TEMP. MONITOR

Figure 1. Layout of the Department of Environmental Science, Rutgers University, research facility at the Camden County Municipal Utilities Authority treatment plant. A typical layout for three 6- metric tonne piles is illustrated.

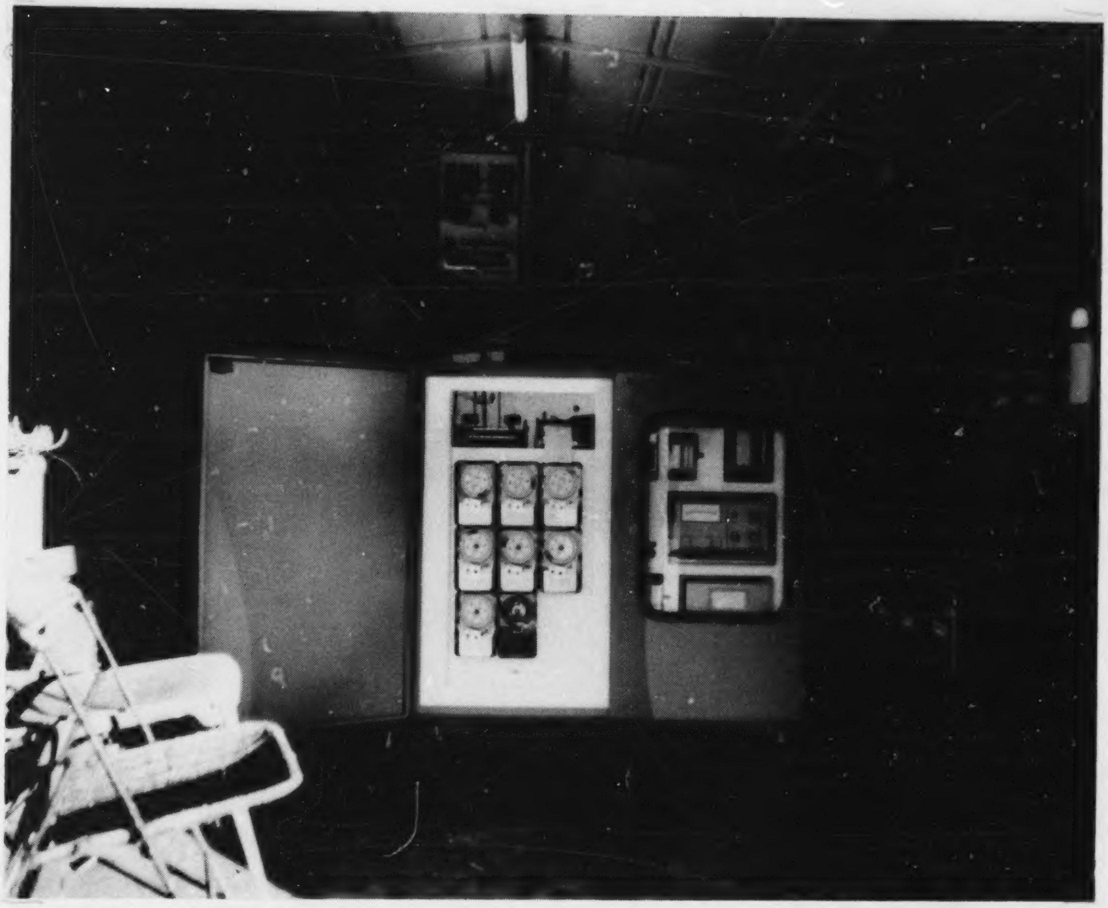


Figure 2. Shed interior showing instrumentation. Photo by F.C. Miller.

(McLanahan Corp., Hollidaysburg, PA). The mixture was discharged to a dump truck for transfer to the pilot facility, 300 meters distant (980 feet).

Mechanical ventilation. Corrugated flexhose (Agway Inc., Englishtown, N.J.) with a diameter of 10.2 cm (4 in.) was used for ventilation ductwork. This was nonperforated, or perforated, as required. A radial blade blower (Dayton, Inc., Chicago, 2C820) with a 1/3 hp motor (Dayton #5K586a) provided ventilation. Unless noted otherwise, the ductwork was fitted to the outlet end of the blower, thus providing ventilation in the forced pressure direction (7).

Assembling the pile. The first step in pile construction was to form a base of woodchips, in which was buried one or more lengths of perforated flexhose (Figure 3). This was connected to the blower via a length of non-perforated flexhose. Over the base was placed the sludge-woodchip mixture, or the sludge-recycled compost mixture, which was covered with woodchips (Figure 4). The piles were parabolic in cross section, a slight longitudinal axis parallel to the flexhose in the smaller piles, and a distinct axis in the larger piles (see Figures 3 and 4).

Blower control - Rutgers strategy. The Rutgers strategy (2-7) utilized a temperature-actuated blower control system consisting of a temperature controller with an adjustable set point (Fenwall Inc., Ashland, MA., Series 551), and a thermistor (Fenwall 28-232806-304) in the pile (Figures 5 and 6). The controller continuously received and interpreted a signal from the thermistor. To dampen response, the thermistor was shielded by threading it into a short length of ¼ in. NPT iron pipe. When the signal indicated a temperature less than the set point the controller actuated the blower through the timer, as scheduled. When the temperature was above the set point the controller directly actuated the blower until ventilation decreased the pile temperature (in the vicinity of the thermistor) to less than the set point. Control is thus "on demand," based on the feedback of a temperature signal.

Monitoring - automatic. Temperature was determined with thermocouples made of 20 gauge copper-constantan wire (Thermoelectric Corp., Saddle Brook, N.J.). Thermocouples were taped to wooden dowels at 0.3m (1 foot) intervals, and the dowels were inserted horizontally into the pile to establish a vertical 0.3 x 0.3m grid (Figure 7). The grid was perpendicular to the long axis of the flexhose. The grid was in the center of the pile, unless noted otherwise. (For photographic examples see Figures 44, 45 and 46.)

Thermocouple leads were organized through the use of subjunction boxes at each pile, through a main junction box, and finally were wired to a recording monitor (Doric Scientific, San Diego, CA., Digitrend 220). The temperature reading was logged every hour.

Gas sampling probes (Figure 8) were inserted into the pile. The probes led, via 0.64 cm (¼ in.) I.D. Tygon tubing, to a condensate trap

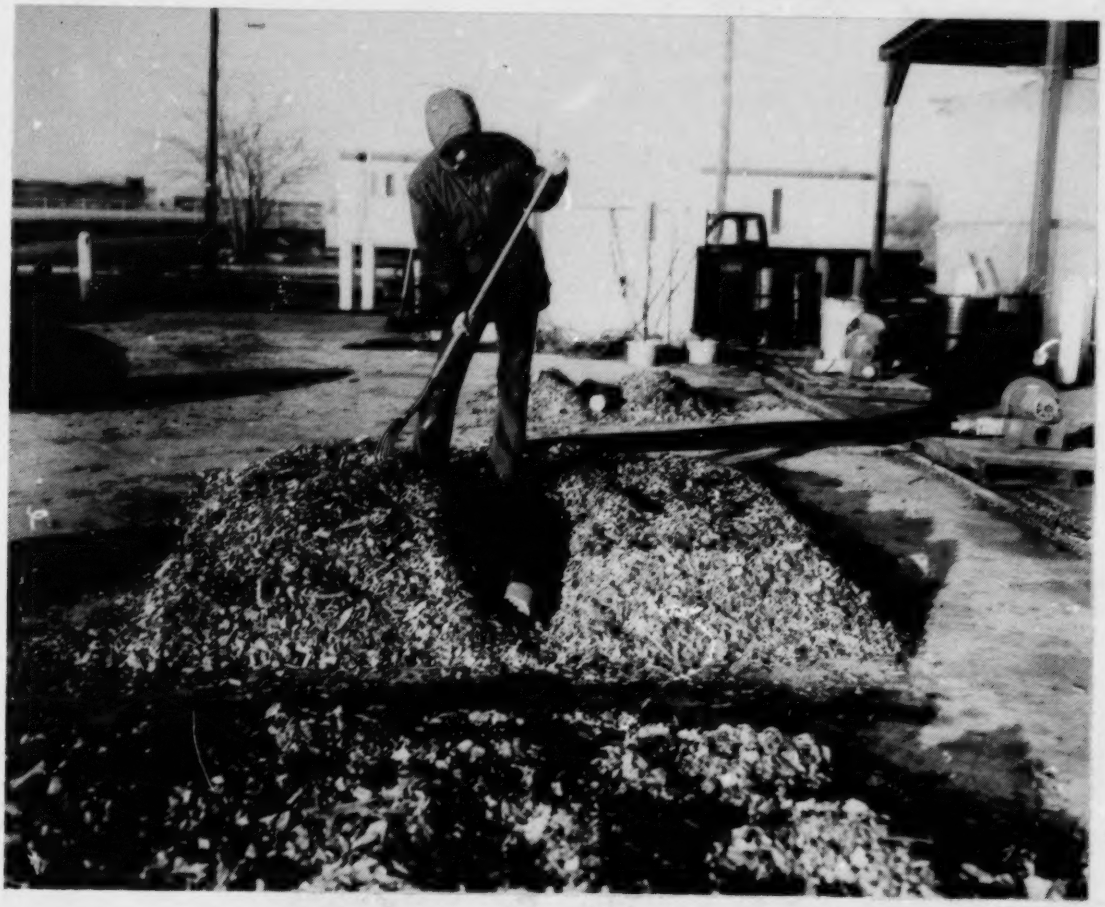


Figure 3. Typical pile construction, preparation of woodchip base. Photo by F.C. Miller.

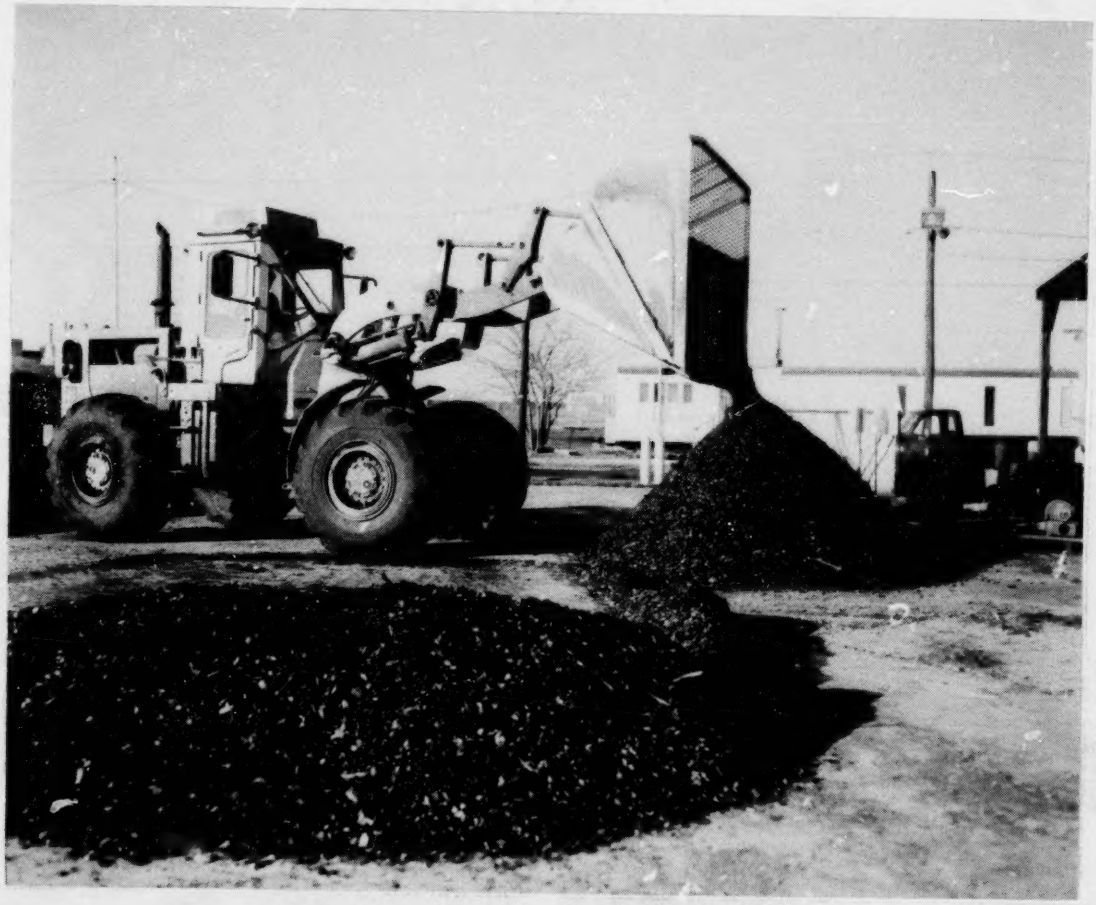


Figure 4. Typical pile construction, placement of sludge-woodchip mixture over the woodchip base. Photo by F.C. Miller.

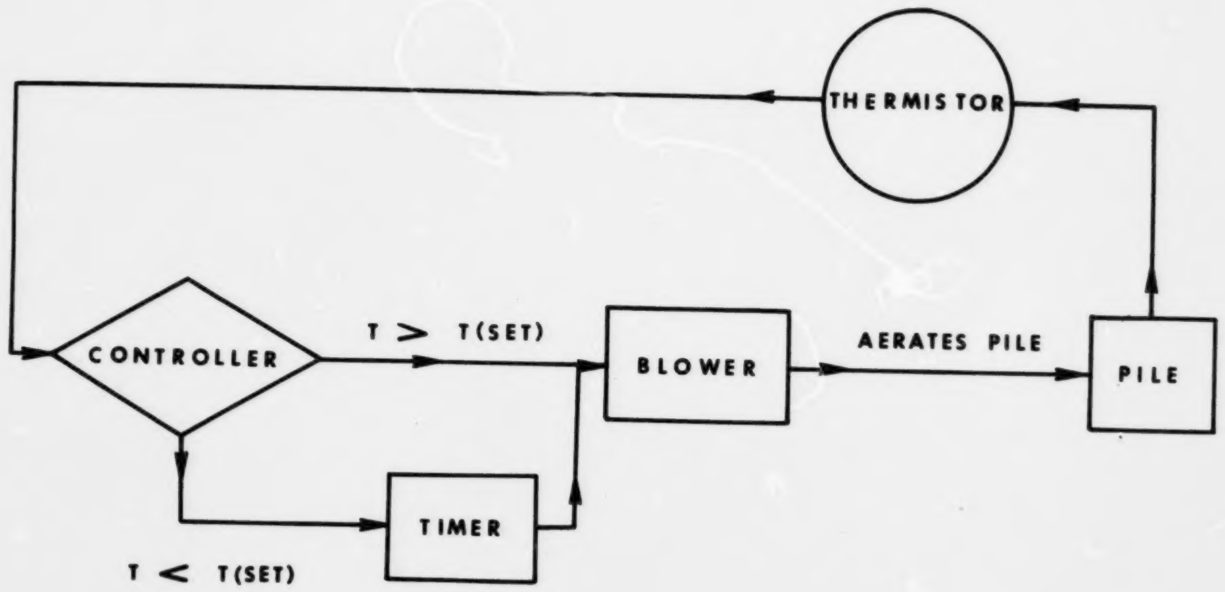
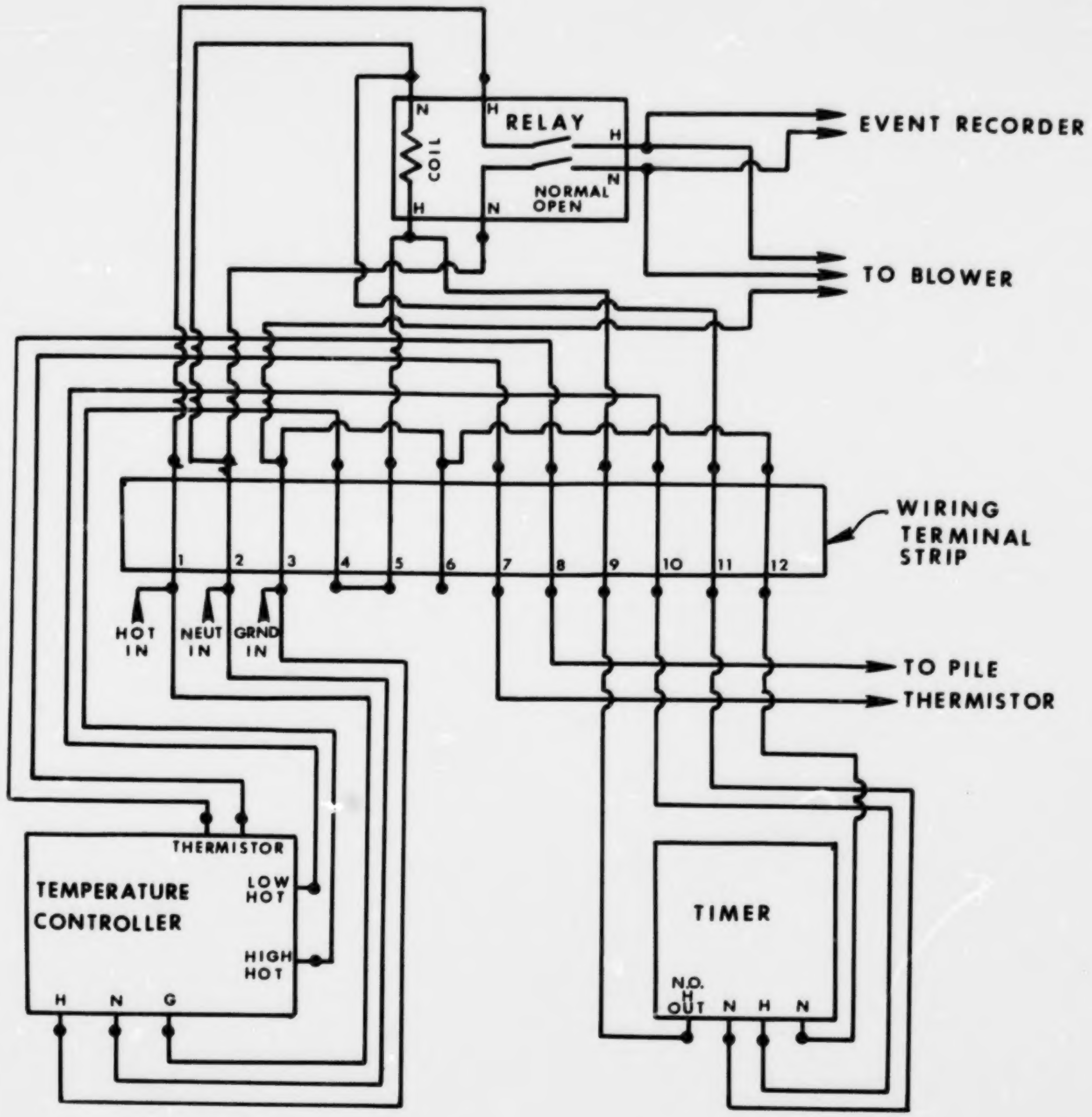

THERMISTOR
CONTROLLER
T > T(SET)
BLOWER
AERATES PILE
PILE
TIMER
T < T(SET)

Figure 5. Blower control logic flow diagram.


RELAY
N
H
COIL
H
N
H
N
NORMAL OPEN
EVENT RECORDER
TO BLOWER
WIRING TERMINAL STRIP
1
2
3
4
5
6
7
8
9
10
11
12
HOT IN
NEUT IN
GRND IN
TO PILE THERMISTOR
THERMISTOR
TEMPERATURE CONTROLLER
LOW HOT
HIGH HOT
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N
G
TIMER
N.O. H OUT
N
H
N

Figure 6. Blower control wiring schematic.

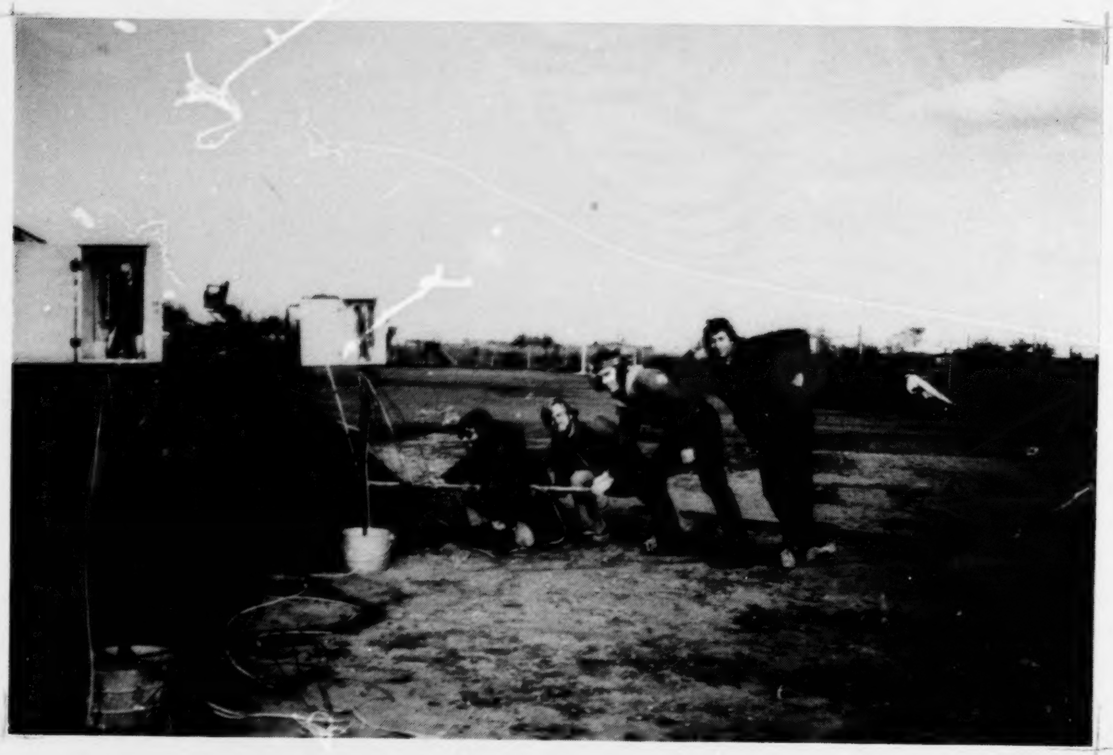

Figure 7. Insertion of a dowel (pile 11C). Fixed to the dowel was the thermistor, and 5 thermocouples at 0.3 m intervals. The personnel were, from left to right, Messrs. Psarianos, MacGregor, Miller and Finstein. Photo by F.C. Miller.

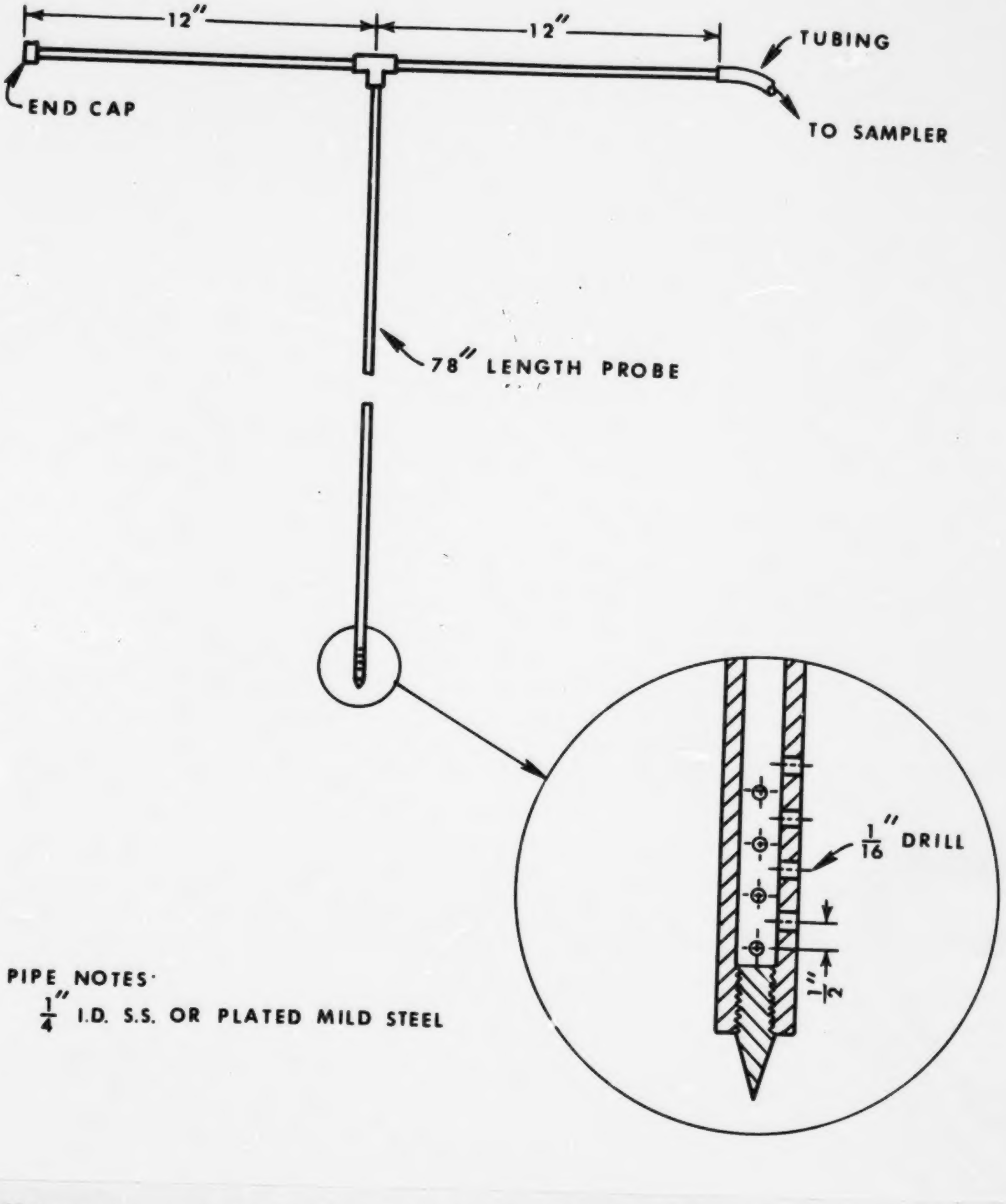
12"
12"
TUBING
END CAP
TO SAMPLER
78" LENGTH PROBE
$\frac{1}{16}$" DRILL
$\frac{1}{2}$"
PIPE NOTES·
$\frac{1}{4}$" I.D. S.S. OR PLATED MILD STEEL

Figure 8. Construction of the gas sampling probe. The dimensions are in inches, based on National Pipe Thread (NPT) standards.

(2L vacuum flask) packed with glass wool, and thence to a seven-point multiplexing system (Figures 9, 10, 11 and 12). The multiplexing system sequentially interrogated up to six different pneumatic inputs using a sample pump of nominal 1.0L/min flow. A nominal 5L/min purge pump maintained flow in the pneumatic lines that were not being interrogated. The seventh sample point was used as an ambient system purge between interrogations. Thirty minute long sample cycles were initiated every four hours (Figure 13).

The gas sample collected by the multiplexer was split for passage through an infrared CO_2 Analyzer (Beckman model 865) and a paramagnetic oxygen analyzer (Beckman model 755). The multiplexer, analyzer, and dual channel stripchart recorder (Beckman model 8720A) were housed in a temperature-controlled cabinet.

Monitoring - manual. A clamshell type posthole digger having a working diameter of 12.7 cm (5 in.) was used to obtain samples. The sample material was put into a plastic bag for transport to the laboratory. Determinations were initiated upon return to the laboratory, usually within 4 hrs of sampling.

Laboratory determinations. Independent "whole sample" and "non-woodchip fraction" moisture content determinations were usually performed. The separation was accomplished by removing non-woodchip material from the woodchips by hand. Except for Section 4 in which the data refer to the non-woodchip fraction, the data in the body of the report refer to the whole sample. A comparison of the moisture contents of the two fractions is given in Appendix A-3.

To determine moisture content, the material was dried at 104°C to constant weight. Moisture content is expressed on a wet weight basis

$$(\%\ \text{moisture} = \frac{\text{wet weight - dry weight}}{\text{wet weight}} \times 100).$$

To prepare sample material for the pH determination, distilled water was added to sieved material to make a slurry. The determination was by pH electrode.

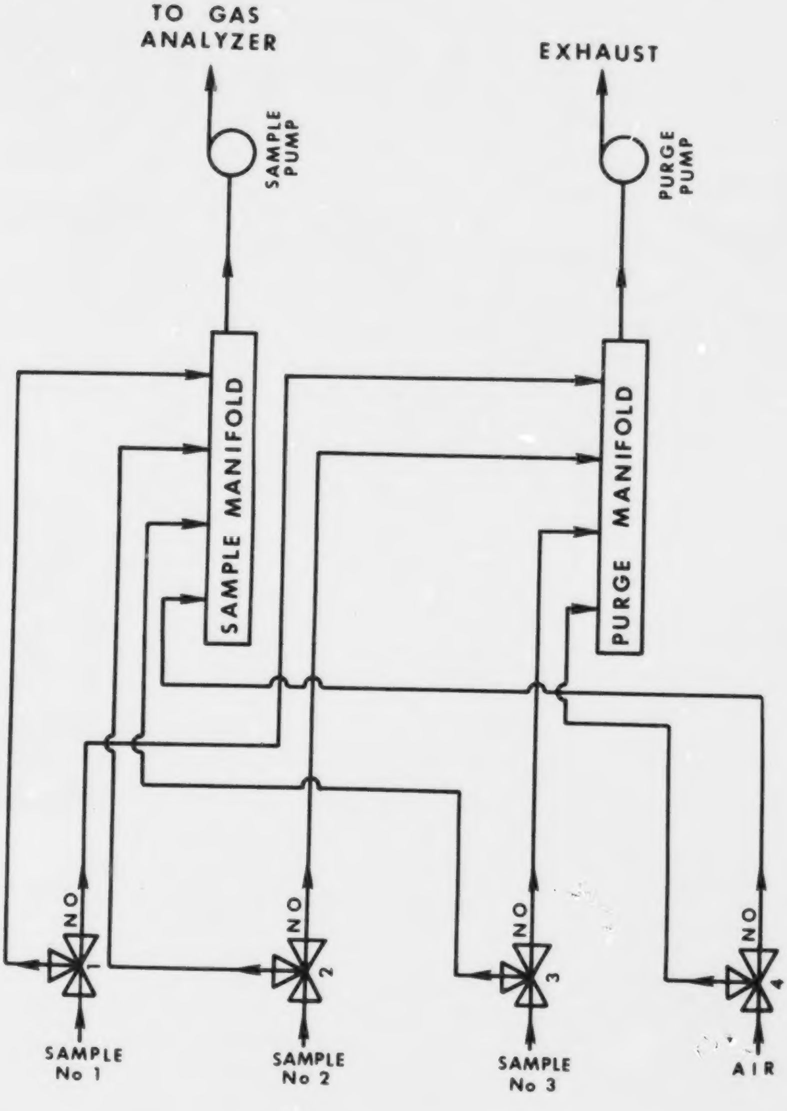
TO GAS ANALYZER
EXHAUST
SAMPLE PUMP
PURGE PUMP
SAMPLE MANIFOLD
PURGE MANIFOLD
NO
NO
NO
NO
1
2
3
4
SAMPLE No 1
SAMPLE No 2
SAMPLE No 3
AIR

Figure 9. Gas multiplexing system, simplified pneumatic flow diagram. The actual multiplexer consisted of six sampling points. Valve no. 4 represents the ambient system purge.

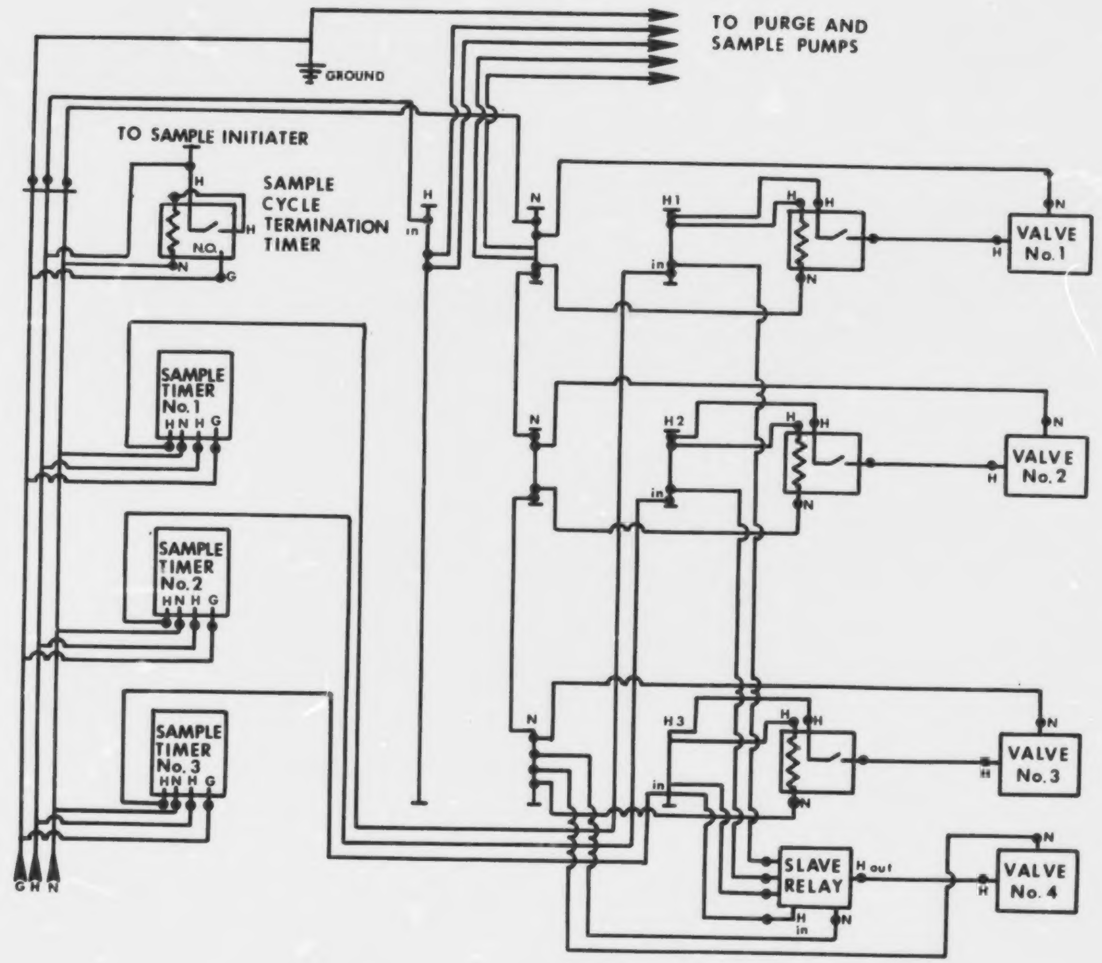
TO PURGE AND SAMPLE PUMPS
GROUND
TO SAMPLE INITIATER
SAMPLE CYCLE TERMINATION TIMER
N.O.
SAMPLE TIMER No. 1
SAMPLE TIMER No. 2
SAMPLE TIMER No. 3
H N H G
H1
H2
H3
in
VALVE No. 1
VALVE No. 2
VALVE No. 3
VALVE No. 4
SLAVE RELAY
H out
H in
G H N

Figure 10. Gas multiplexing system, simplified electrical schematic. The actual multiplexer consisted of six sampling points. Valve no. 4 represents the ambient system purge.

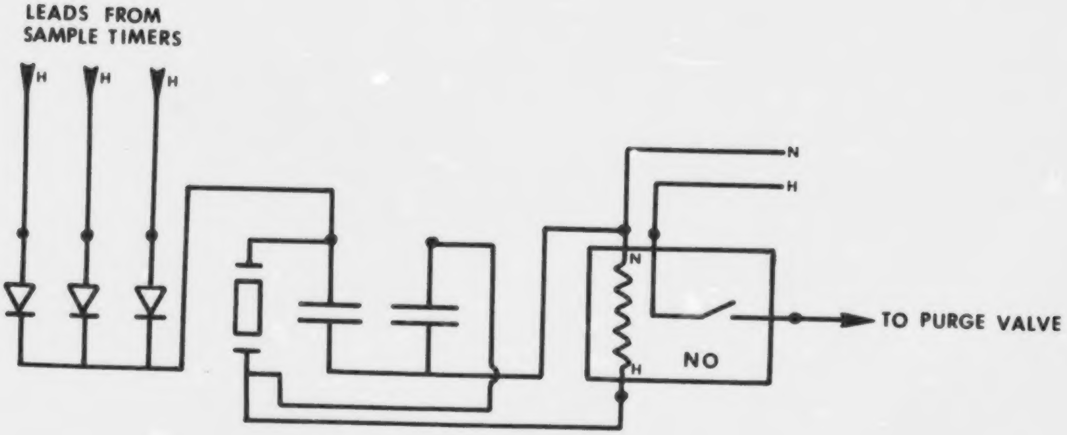
LEADS FROM
SAMPLE TIMERS
H
H
H
N
H
N
H
NO
TO PURGE VALVE

Figure 11. Fabrication of slave relay (see Figure 10). Parts list: Diodes (3), WER-17; resistor, 1K 10% (76131RC PW1C); capacitor, SPRAGUE TE-1509 20-150DC USA-7317H; relay, POTTER & BRUNFIELD KA501 110 VDC.

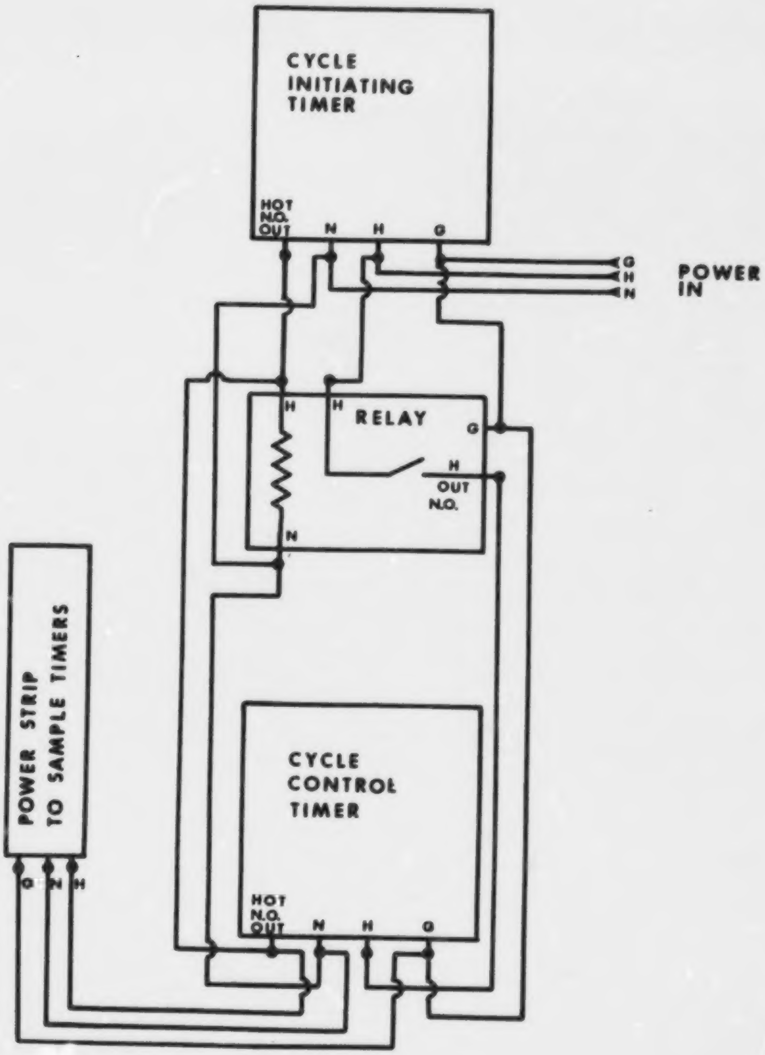
CYCLE INITIATING TIMER
HOT N.O. OUT
N
H
G
G
H
N
POWER IN
H
H
RELAY
G
H
OUT N.O.
N
POWER STRIP TO SAMPLE TIMERS
G
N
H
CYCLE CONTROL TIMER
HOT N.O. OUT
N
H
G

Figure 12. Gas sampling cycle actuation system.

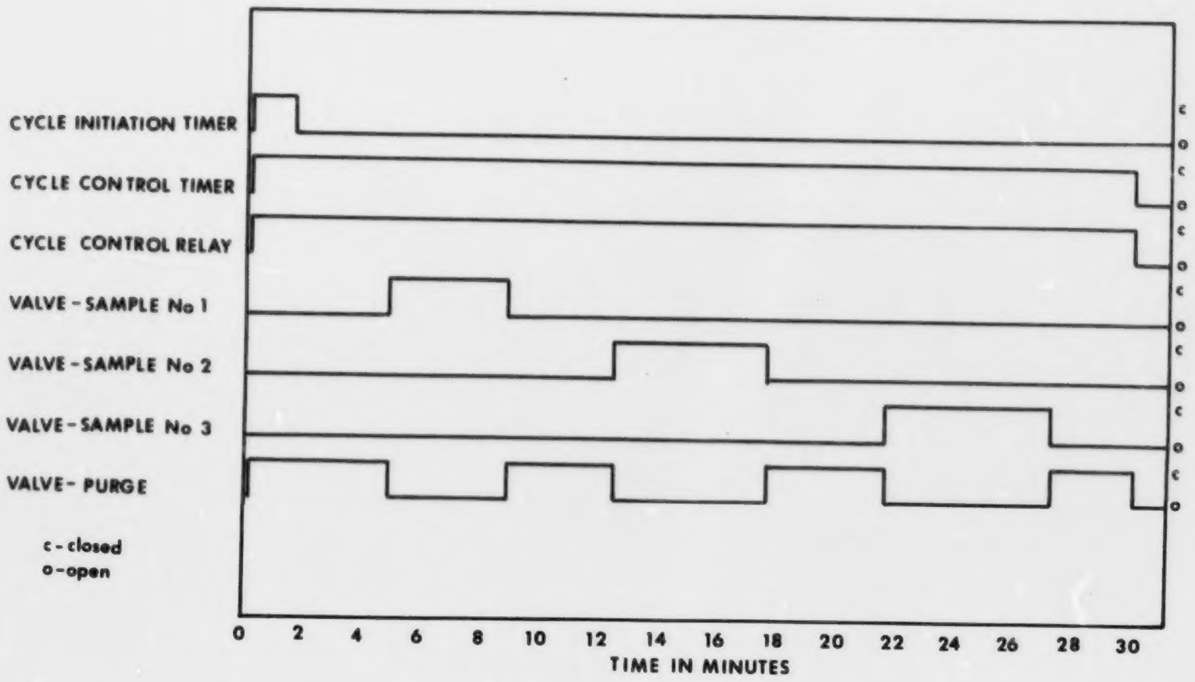

Figure 13. Gas sampling cycle actuation graphic representation.

SECTION 3

COMPARISON BETWEEN THE RUTGERS AND BELTSVILLE CONTROL STRATEGIES: OBSERVATION AND INTERPRETATION OF SYSTEM BEHAVIOR

IMPORTANCE OF THE COMPARISON

Comparative study of the Rutgers (2-7) and Beltsville (8-11) strategies has universal relevance to composting process design and control. This is because i. composting processes are based on the self-heating microbial ecosystem, ii. these strategies represent fundamentally different approaches to the management of this ecosystem, iii. the comparative analysis yields a coherent theory of the physical, chemical, and biological interactions governing the dynamics of this ecosystem.

The basic experimental design was to isolate strategy as the only variable, by implementing both strategies in a common configuration (static pile). This permitted orderly interpretation of the data. The distinction between strategy and configuration was already drawn (Section 1).

MATERIALS AND METHODS SPECIFIC TO SECTION 3

Ventilation

For pile 9B (Beltsville Process) the blower was operated in the vacuum-induced direction, solely as scheduled by timer. A condensate trap was interposed between this blower and its piles (Figure 14). For piles 7, 8, and 9A (Rutgers strategy) the blowers were operated in the forced-pressure direction, as actuated by the temperature feedback control system.

Pile Construction and Control, and Weather

The physical features of the piles and the ambient weather conditions are summarized in TABLE 2. Variations in the control of the ventilation system were as follows:

Timer schedule (uninterruped min on/15 min)

Pile 7: time zero - hr 500, 1.75/15
Pile 8: time zero - hr 500, 1.25/15
Pile 9A: time zero - hr 120, 1.5/15; hr 120 - hr 240, 1.25/15;
hr 240 - 500, 0/15
Pile 9B: time zero - hr 70, 4/15; hr 70 - hr 500, 3/15

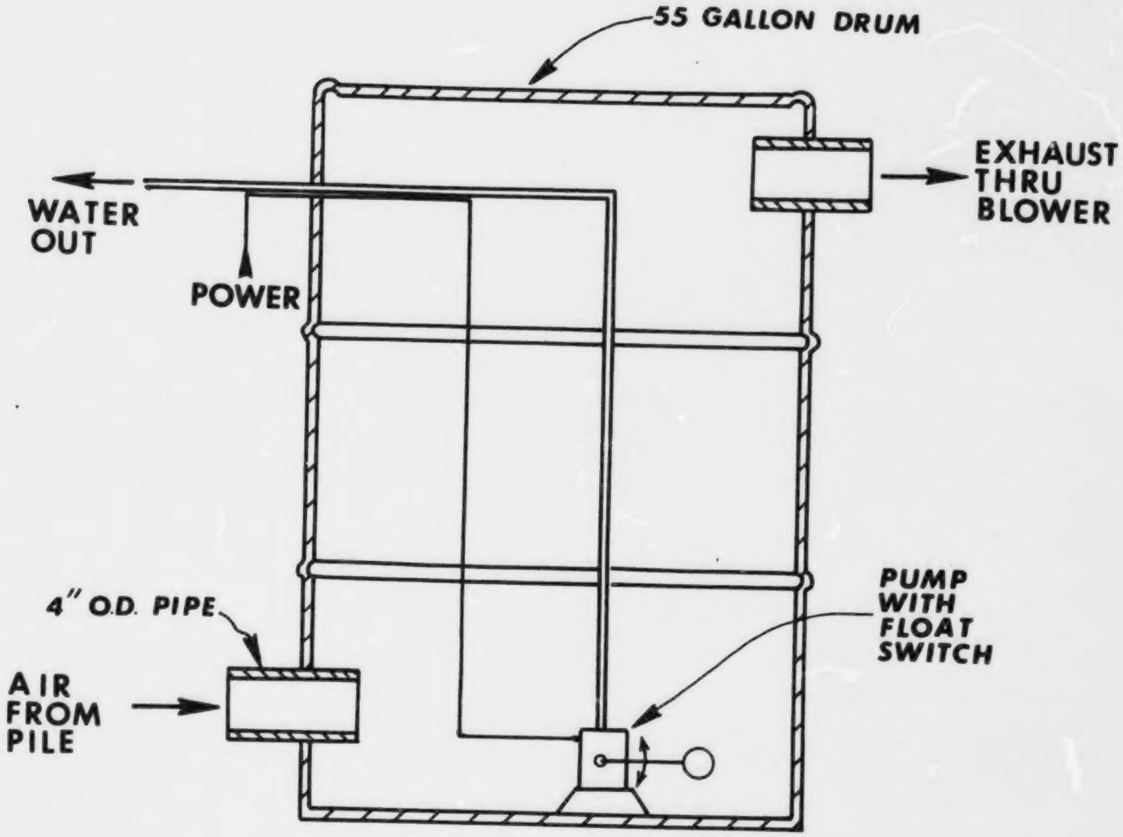
55 GALLON DRUM
EXHAUST THRU BLOWER
WATER OUT
POWER
4" O.D. PIPE
PUMP WITH FLOAT SWITCH
AIR FROM PILE

Figure 14. Condensate trap used for the pile (9B) managed according to the Beltsville process.

Thermistor placement

Pile 7: time zero - hr 56, position 1; hr 56-500, position 6
Pile 8: time zero - hr 500, position 6
Pile 9A: time zero - hr 44, position 1; hr 44-500, position 6
Pile 9B: not applicable

Temperature set point (i.e., setting of the temperature controller)

Pile 7: time zero - hr 500, 45°C
Pile 8: time zero - hr 500, 45°C
Pile 9A: time zero - hr 76, 45°C; hr 76 - hr 500, 48°C
Pile 9B: not applicable

The cross-sectional representation of the piles are given in Figures 15, 16, 17 and 18.

RESULTS

Three of the piles were controlled according to the Rutgers strategy (piles 7, 8, and 9A), and one according to the Beltsville Process (pile 9B). The pile weights were: pile 7, 6 tonnes; pile 8, 27 tonnes; pile 9A, 36 tonnes; pile 9B, 36 tonnes. Piles 9A and 9B (Figure 19) were assembled within two days of each other, to provide a direct comparison of the alternative approaches to process control.

Blower Operation

Blower operation is represented in Figures 20, 21, 22, and 23. Temperature feedback control (Rutgers piles only) commenced as follows: pile 7, hr 56; pile 8, hr 10; pile 9A, hr 10. The maximum blower operation (% time on) and the time at which the maximum operation occurred was, respectively: 60%, hr 110; 40%, hr 100, 100%, hr 96 to 135. In pile 7 the period of feedback control ended at hr 344, at which time "demand" for the blower was less than that scheduled by the timer. Thereafter, timer-scheduled operation resumed. In pile 8 the return to schedule operation occurred at hr 170. The timer to pile 9A was disconnected at hr 240, eliminating the resumption of timer-scheduled blower operation when feedback control ended. Judging from the dwindling amount of blower operation time, timer scheduled operation for this pile would have resumed prior to hr 380.

The blower to the Beltsville pile was scheduled for operation 27% of the time early in the run (Figure 23). At hr 70 this was decreased to 20%, as the O_2 content exceeded that suggested for this process (9).

Pile Temperature

In the Rutgers piles the median values were a few degrees higher than the assigned set point (e.g. for pile 7, 47°C vs 45°C), and only 10% to 13% of the individual observations exceeded 60°C. In the Beltsville pile the median was 70°C, and 91% of the individual observations exceeded 60°C. The observations on temperature and other parameters are summarized in TABLE 3. The individual temperature graphs are given in Appendix

TABLE 2. PILE DESCRIPTION - PHYSICAL ASPECTS AND WEATHER CONDITIONS

Item	Pile 7	Pile 8	Pile 9A	Pile 9B
Trial period[*]				
Start	21 Apr	27 May	9 Jul	11 Jul
End	12 May	9 June	1 Aug	1 Aug
Ambient air temperature (°C)[†]				
High	21	27	32	32
Low	9	15	21	21
Mean	15	21	27	27
Range	2 to 31	10 to 31	16 to 36	16 to 36
Rainfall				
Amt (cm)	9.3	3.3	13.1	10.0
Events (no.)	10	6	7	6
Pile dimensions in meters (LxWxH)				
(Woodchip base)	3.0 x 2.7 x 0.2	13 x 2.1 x 0.2	13 x 2.4 x 0.2	14 x 5.5 x 0.2
(Overall[‡])	4.9 x 4.3 x 2.0	15 x 4.3 x 2.0	15 x 4.9 x 2.1	14 x 5.2 x 2.1
Pile weight (tonnes)	6	27	36	36
Perforated flexhose				
Segments (no.)	1	6	6	2
Lengths (m)	2.7	5.6	5.6	12.2
Blowers (no.)	1	6	6	1
Direction of ventilation[§]	Forced pressure	Forced pressure	Forced pressure	Vacuum induced
Basis of control[§]	Temp feedback	Temp feedback	Temp feedback	Timer schedule

---

[*] The dates refer to 1980. [†] High = mean of the daily highs: low = mean of the daily lows; mean = mean of the daily means; range = overall range of the daily highs and lows. [‡] Dimensions before adding a covering of woodchips 25 to 30 cm thick. [§] Forced pressure and temp feedback = Rutgers strategy; vacuum-induced and timer schedule = Beltsville process.

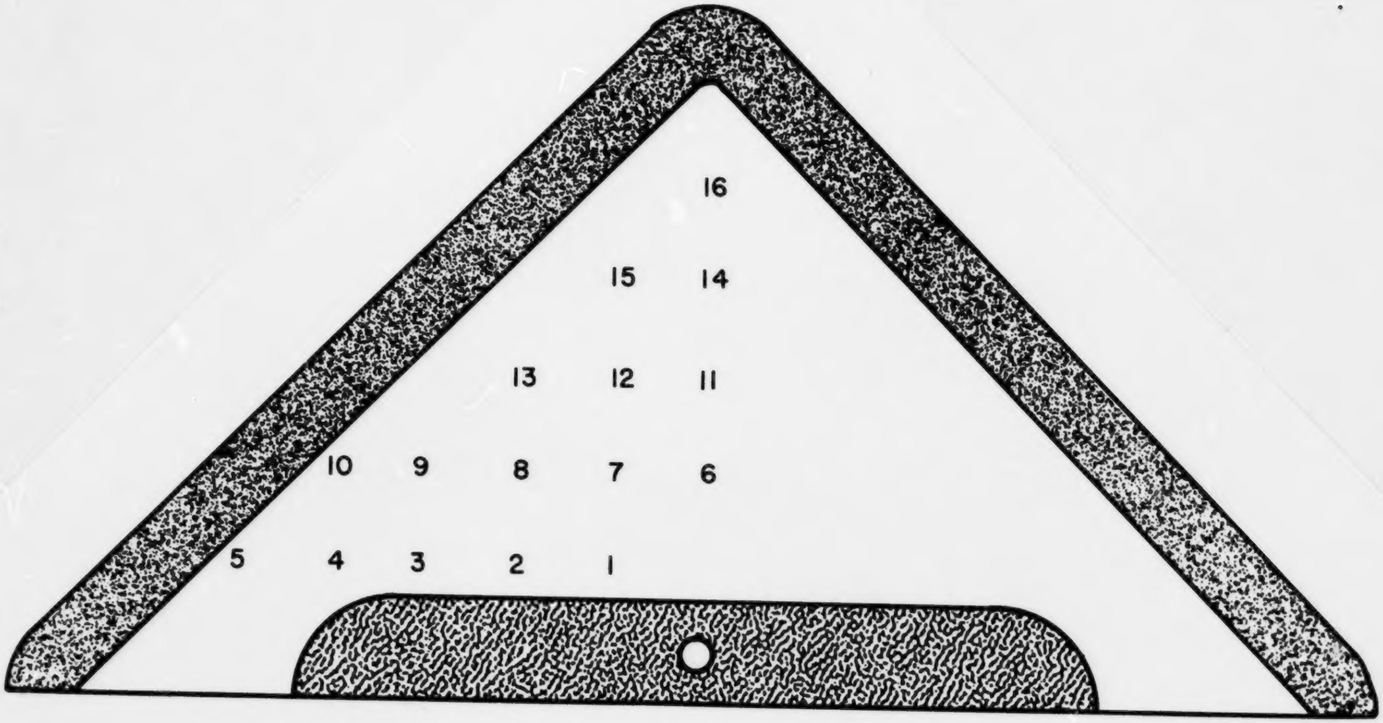

Figure 15. Pile 7, cross-sectional representation: textured area, woodchip cover and base; clear area, sludge-woodchip mixture; circle, perforated flexhose. The numbers indicate monitoring and control positions: thermocouples, positions 1 through 16; gas sampling probes, adjacent to positions 6 and 14; control thermistor, position 6 for most of the run (see Table III-3). The blower was operated in the forced-pressure mode.

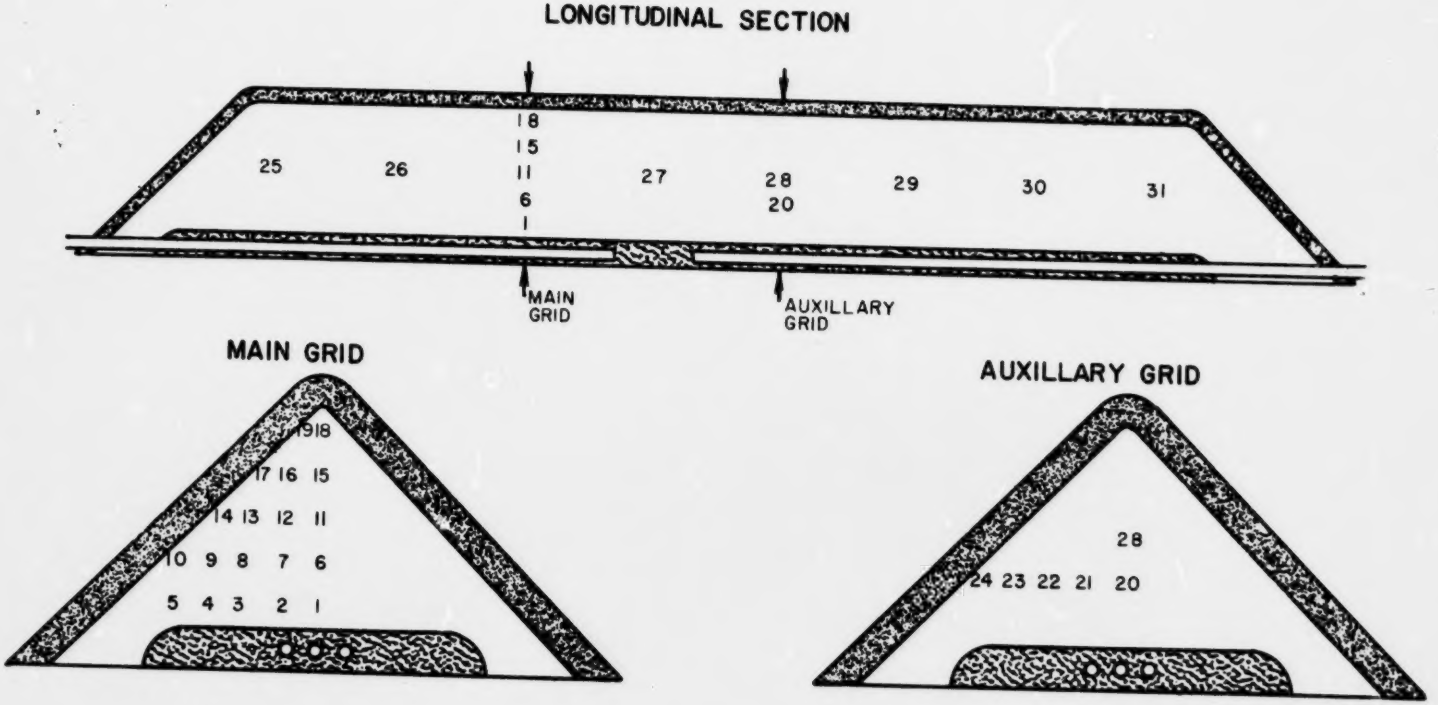
LONGITUDINAL SECTION
25
26
18
15
11
6
1
27
28
20
29
30
31
MAIN GRID
AUXILLARY GRID
MAIN GRID
19 18
17 16 15
14 13 12 11
10 9 8 7 6
5 4 3 2 1
AUXILLARY GRID
28
24 23 22 21 20

Figure 16. Pile 8, cross-sectional representation: textured area, woodchip cover and base; clear area, sludge-woodchip mixture; circles, perforated flexhoses. The numbers indicate monitoring and control positions: thermocouples, positions 1 through 31; gas sampling probes, adjacent to positions 11, 20 and 28; control thermistor, position 6. The circles and tubes in the woodchip base represent flexhoses. The blowers were operated in the forced-pressure mode.

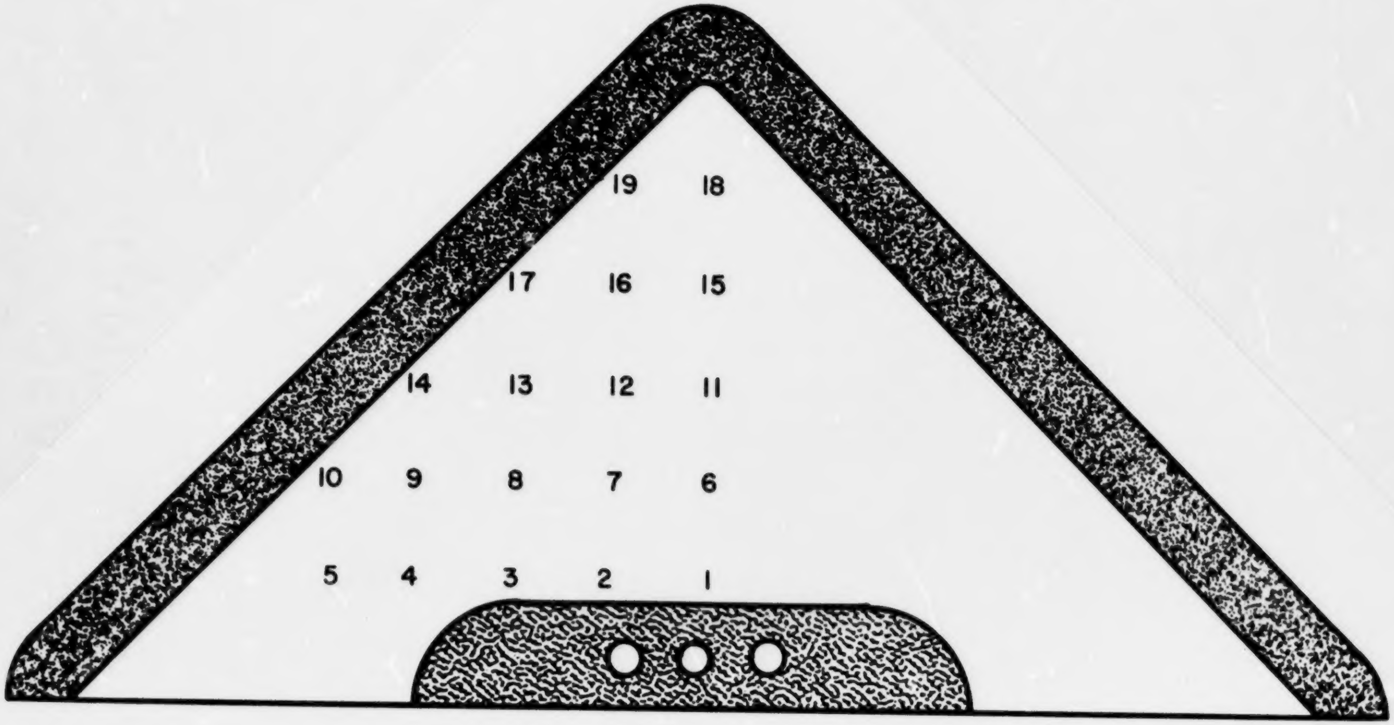

Figure 17. Pile 9A, cross-sectional representation: textured area, woodchip cover and base; clear area, sludge-woodchip mixture; circles, perforated flexhoses. The numbers indicate monitoring and control positions: thermocouples, positions 1 through 19; gas sampling probes, adjacent to positions 7 and 16; control thermistor position 6 for most of the run (see text). The thermocouple grid was positioned 6m from an end of the pile. The blowers were operated in the forced-pressure mode.

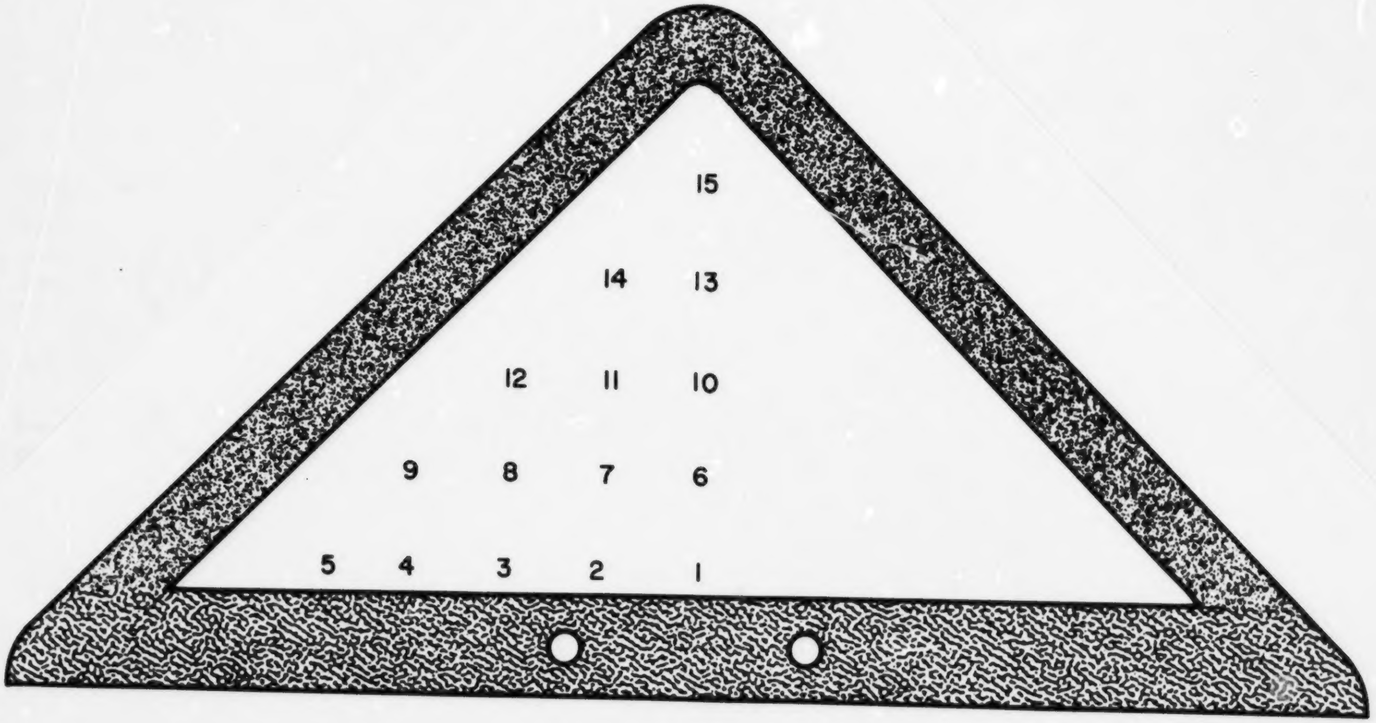

Figure 18. Pile 9B, cross-sectional representation: textured area, woodchip cover and base; clear area, sludge-woodchip mixture; circles, perforated flexhoses. The numbers indicate monitoring positions: thermocouples, positions 1 through 15; gas sampling probes, adjacent to positions 7 and 14. The thermocouple grid was positioned 6m from the end of the pile proximal to the blower. The blower was operated in the vacuum-induced mode and controlled solely by timer.

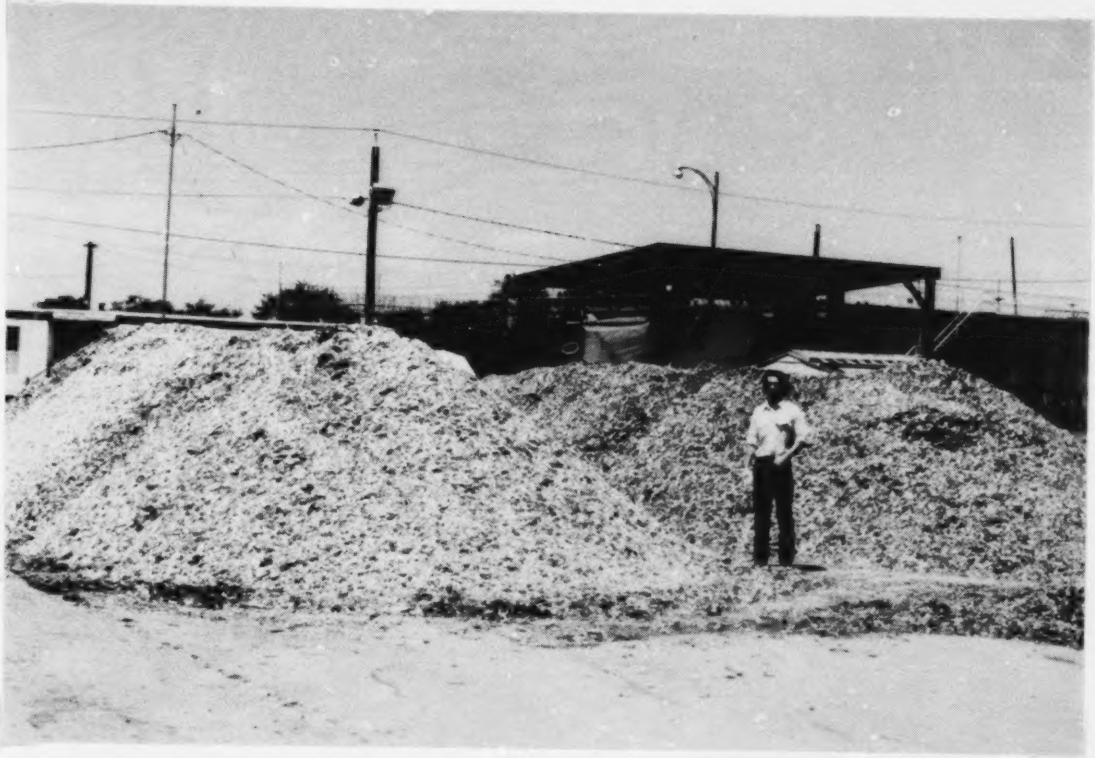

Figure 19. Pile 9B (left) and pile 9A (right). Photo by James A. Miller.

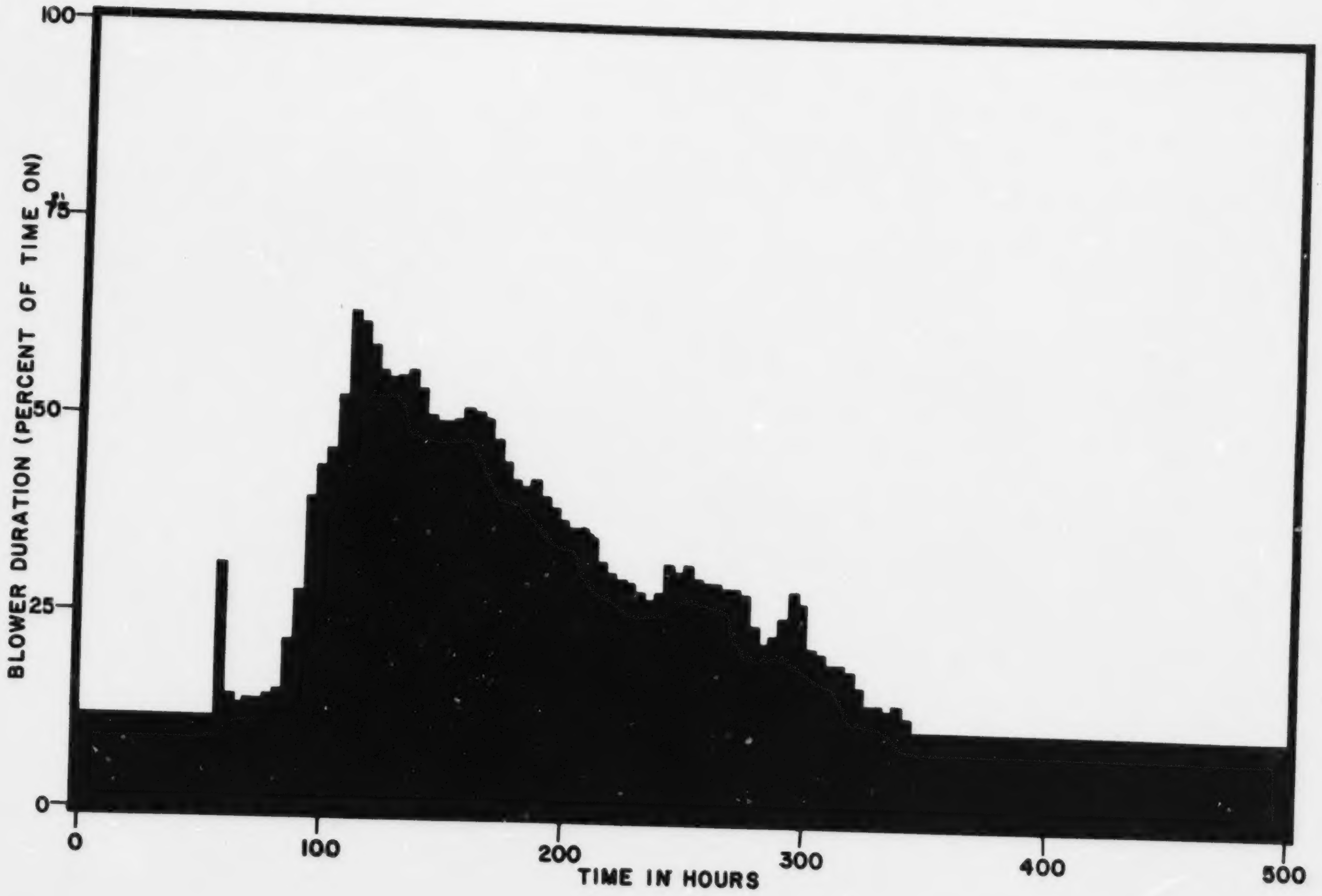

Figure 20. Pile 7, blower operation. The baseline represents operation as scheduled by timer, and the area above the baseline represents operation through the temperature-feedback control system.

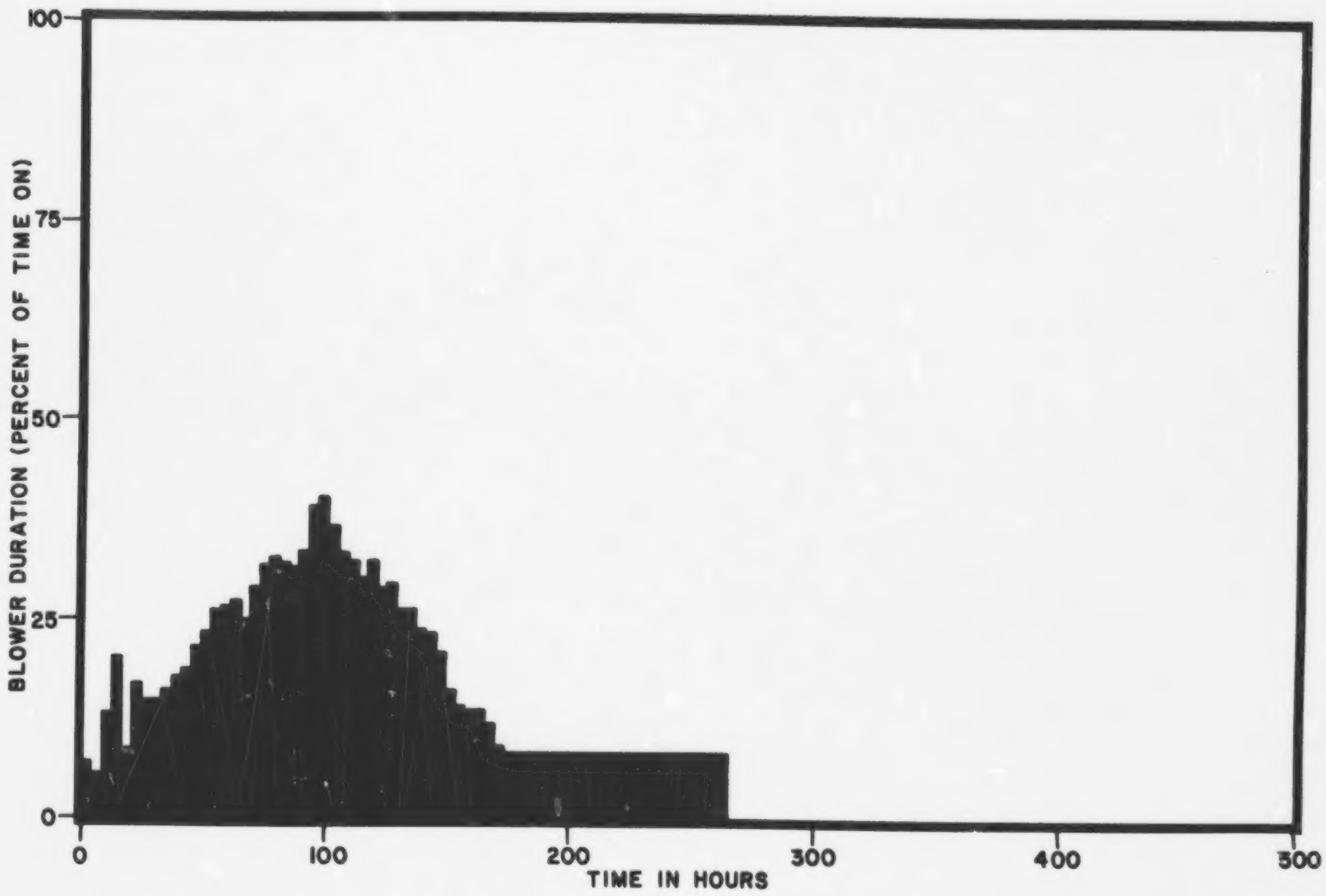

Figure 21. Pile 8, blower operation. The baseline represents operation as scheduled by timer, and the area above the baseline represents operation through the temperature-feedback control system.

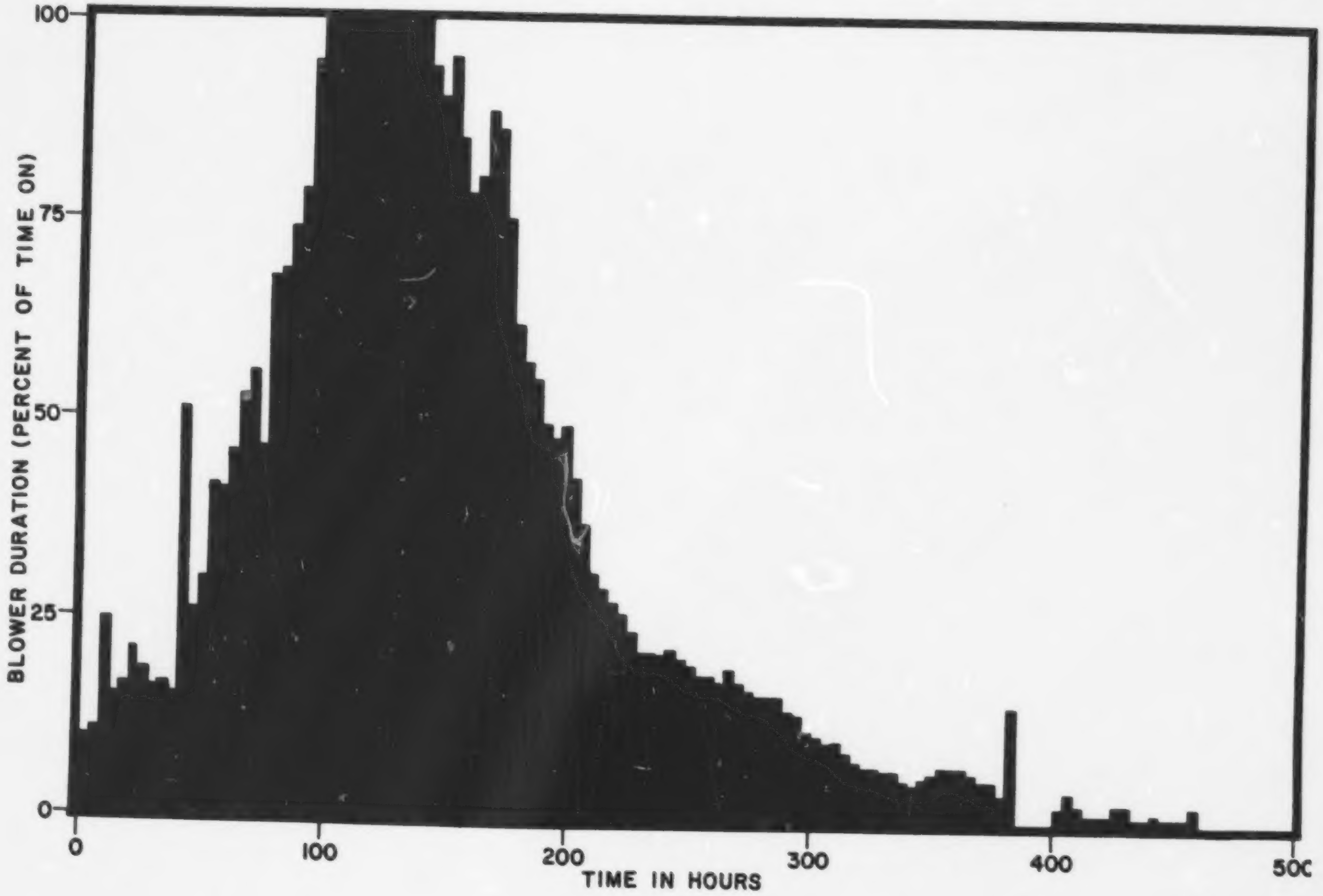

Figure 22. Pile 9A, blower operation. The baseline (hr zero to 10) represents operation as scheduled by timer, and the area above the baseline represents operation through the temperature-feedback control system. The timer was disconnected at hr. 240.

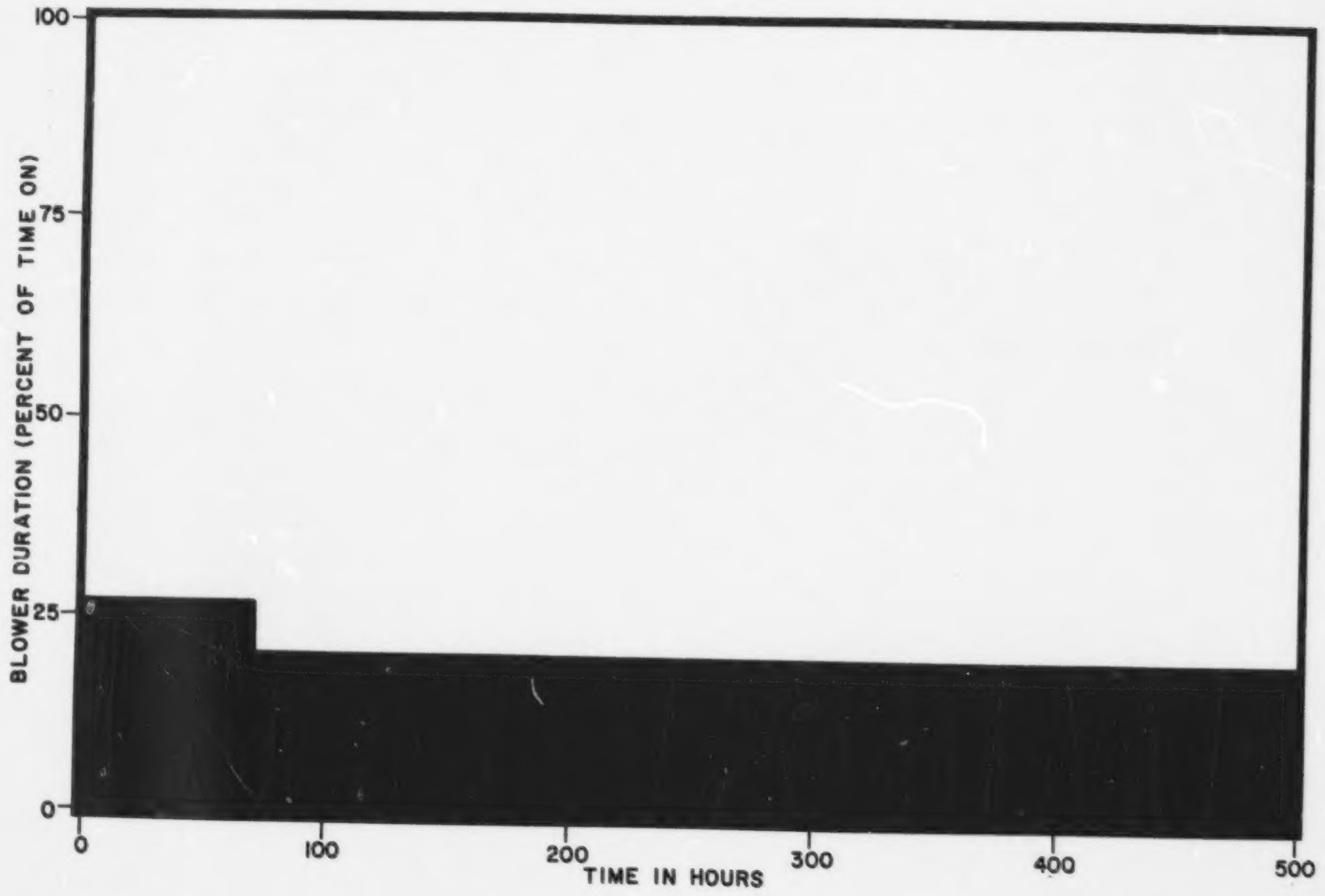

Figure 23. Pile 9B, blower operation as scheduled by timer.

TABLE 3. SUMMARY OF THE DATA FROM SECTION 3

	Process control strategy			
	Rutgers			Beltsville
	Pile 7	Pile 8	Pile 9A	Pile 9B
Temperature*				
Period (hrs)	56-344	10-170	10-380	100-500
Range (°C)	26-68	19-70	24-68	45-82
Median (°C)	47	48	53	70
Observations (no.)	1102	728	1755	1519
% Observations ≥60°C	11	10	13	91
Interstitial gases				
Period (hrs)	0-388	0-268	0-500	0-500
O_2 Range (%)	14.5-21	6.0-21	8.0-21	12-21
O_2 Median (%)	20.0	18.5	19.8	20.0
Observation (no.)	152	204	246	340
CO_2 Range (%)			0-9	0-7
CO_2 Median (%)			1.0	<0-0.1
Observations (no.)			246	240
Moisture content (%)				
Time zero (%)	62	56	67	65
Selected observation				
(hr)	344	190	310	500
(%)	29	24	33	61

---

*For piles 7, 8, and 9A the summary is for the period of temperature feedback control. For pile 9B the summary excludes the period of temperature come-up.

A-1.

In the Rutgers piles the data from the innermost vertical series of probes (positioned generally in a line above an air duct) indicate the establishment of a systematic temperature gradient in the direction (upward) of airflow (Figures 24, 25, and 26). In the Beltsville pile the lower members of the innermost series (not directly in a line above an air duct-see Figure 18) recorded a weak gradient in the direction (downward) of airflow (Figure 27). A gradient is absent at the upper end of this series (Figure 28), which represents the pile apex. A more well-defined gradient was established at the adjacent vertical series of probes (Figure 29), which was directly in a line above a duct-see Figure 18). This gradient was shallow and erratic, however, compared to those in the Rutgers piles. The temperature gradient patterns are summarized in Figure 30.

In the Rutgers piles the temperature at the thermistor position slightly "overshot" the set-point at around the time that blower control passed from timer-schedule to temperature feedback (i.e. at the start of the period of feedback control). The relatively erratic temperature record of Pile 9A during this transition is attributed to control changes at this time (see Pile Construction and Control, and Weather). Nonetheless, starting at approximately hr 140, in this pile also the temperature at the termistor position stabilized at the set point-level. After termination of feedback control, and with the resumption of timer-scheduled ventilation (piles 7 and 8 only), the temperature declined rapidly. Where scheduled ventilation was not resumed (pile 9A) the temperature fluctuated slightly, but no particular trend set in.

Pile Atmosphere

All of the piles were monitored for O_2, but only piles 9A and 9B were also monitored for CO_2. Since the three Rutgers piles behaved similarly with respect to O_2, only the observations for Pile 9A, which involved both gases, are reported here (Figures 31, 32, 33 and 34). The other O_2 data are given in Appendix A-2.

In the Rutgers pile the minimum O_2 content (upper position) was 8% (hr 26), and in the Beltsville pile (upper position) this was 12% (hr 70). Minimum O_2 values at the lower probes were 15% and 19% (hrs 380 and 70, respectively). The O_2 and CO_2 plots are generally complimentary in that relatively high values of O_2 and low values of CO_2 occurred simultaneously, and vice-versa.

Moisture Content

The moisture content data reported here are for the whole sample (includes woodchips). For a comparison with the non-woodchip fraction, see Appendix A-3.

The respective starting moisture contents were (%): 62, 56, 67, and 65 (Figures 35 and 36). In the three Rutgers piles drying was substantial in that by termination the moisture content decreased to low levels (29%, 24% and 29%). Relative to piles 7 and 8, the onset of drying in pile 9A was delayed. Once drying commenced, however, it progress-

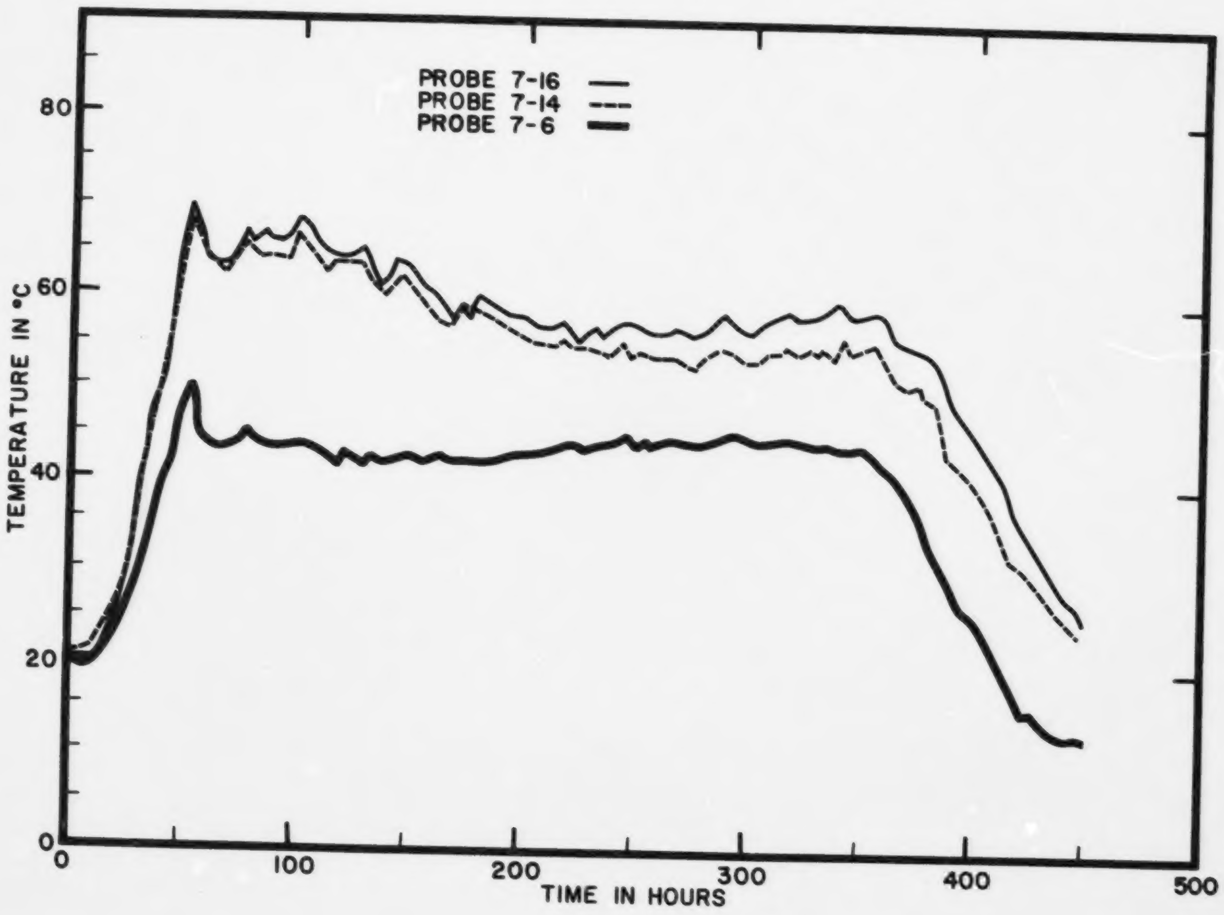

Figure 24. Pile 7, temperature at the innermost vertical series of thermocouples.

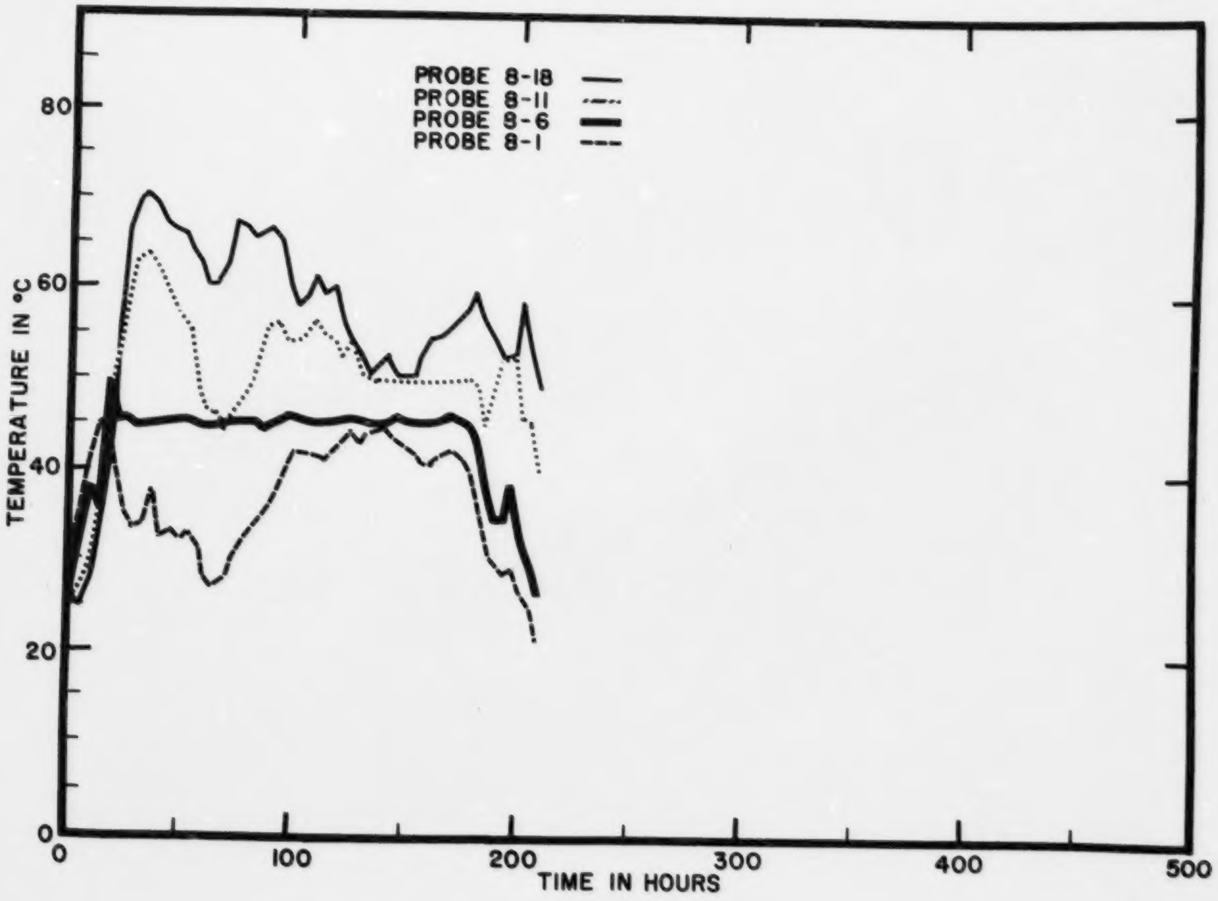

Figure 25. Pile 8, temperature at the innermost vertical series of thermocouples (main grid).

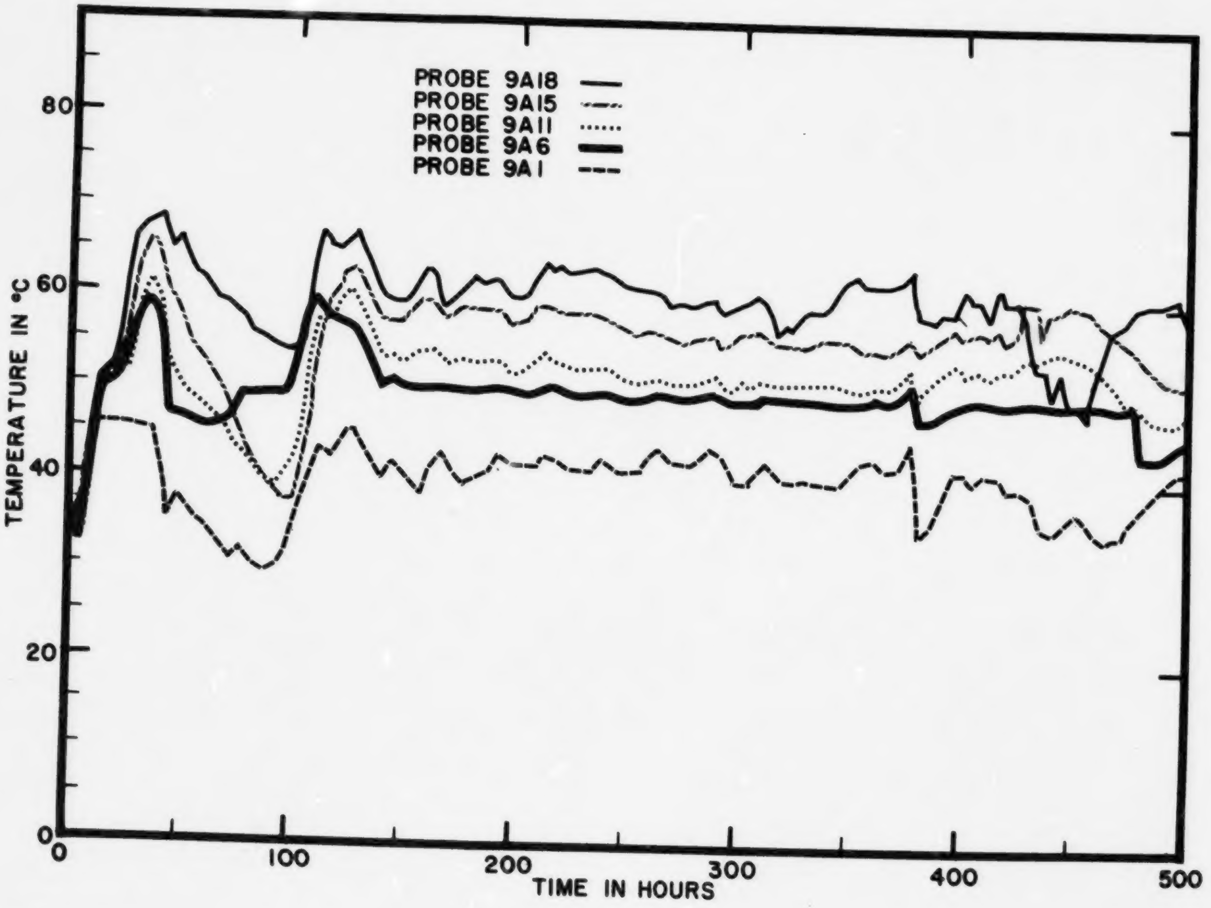

Figure 26. Pile 9A, temperature at the innermost vertical series of thermocouples.

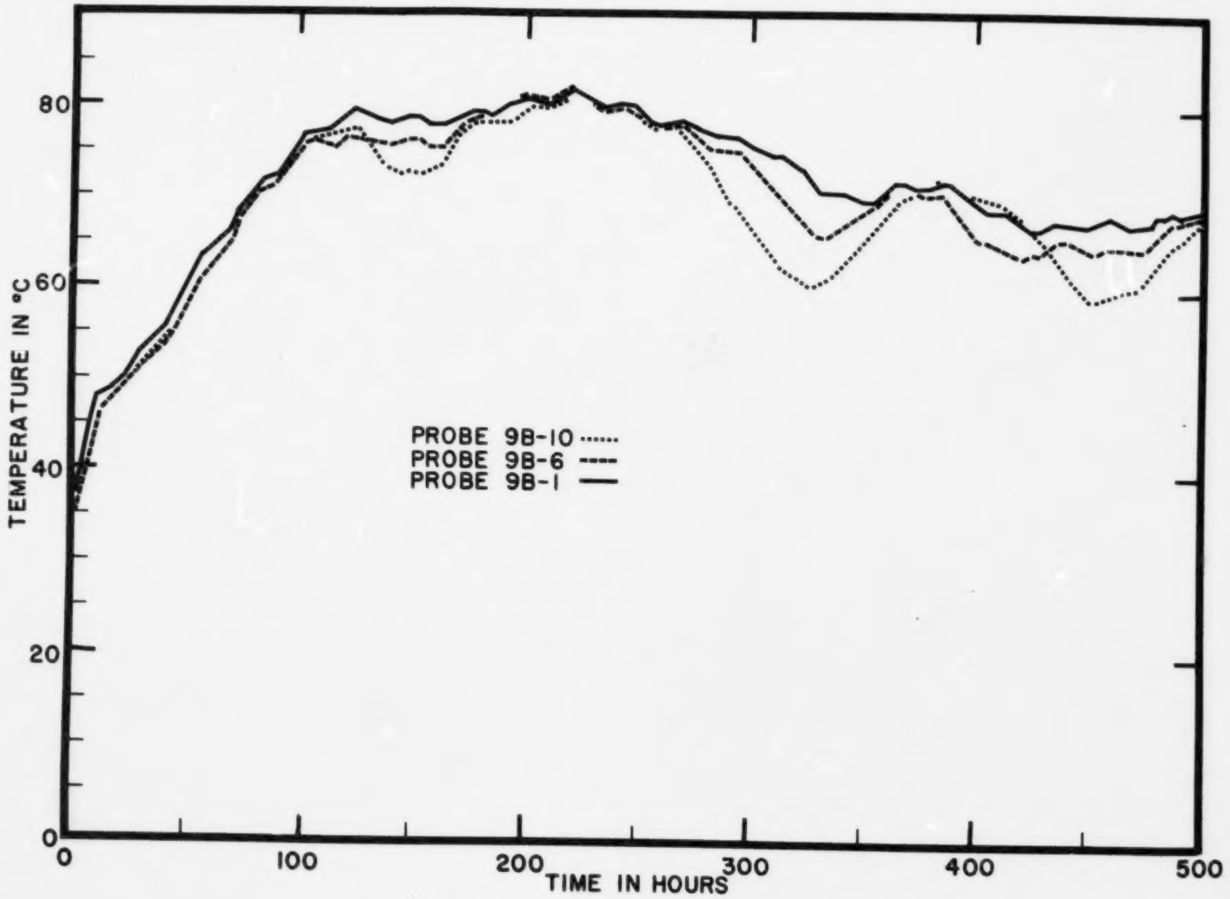

Figure 27. Pile 9B, temperature at the lowest three thermocouples of the innermost vertical series.

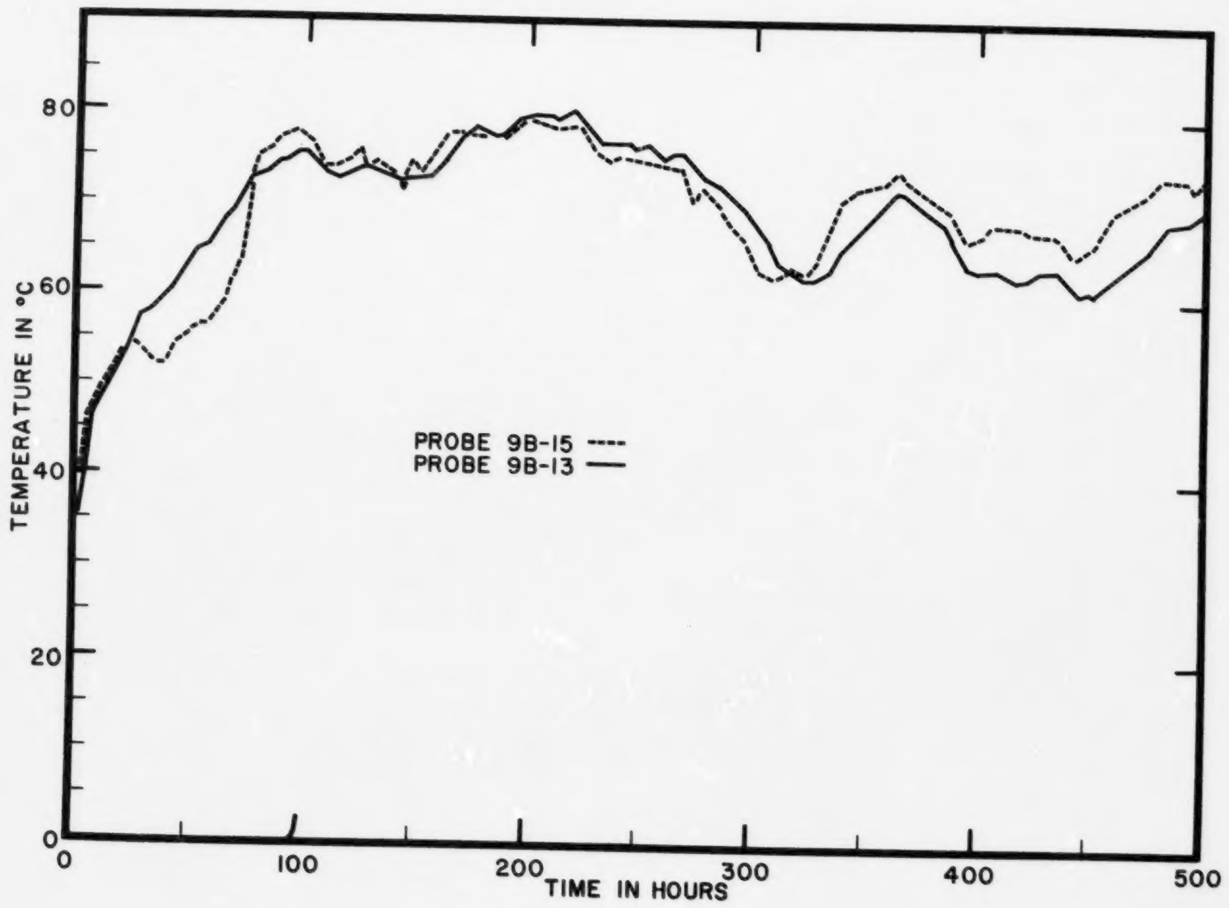

Figure 28. Pile 9B, temperature at the highest two thermocouples of the innermost vertical series.

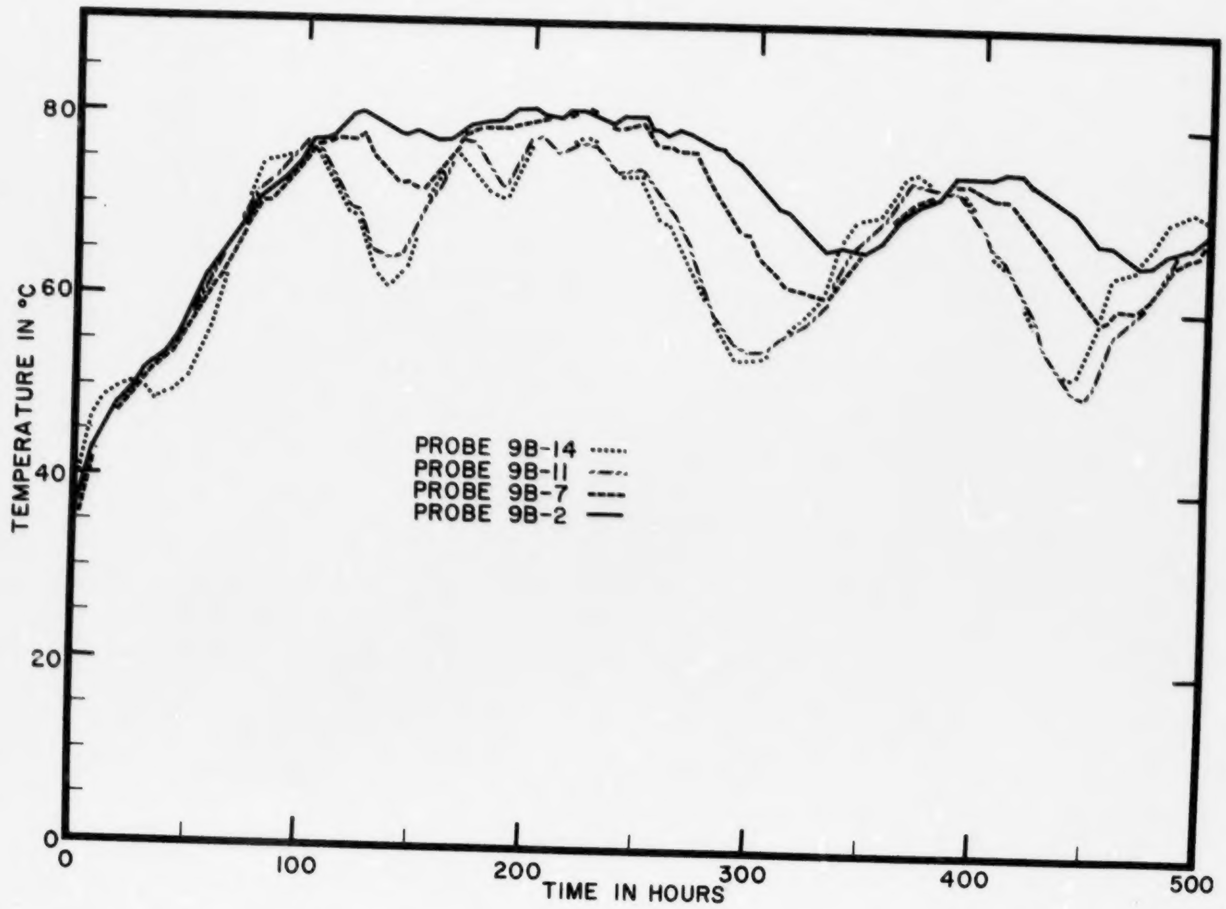

Figure 29. Pile 9B, temperature at the thermocouples of the next-to innermost vertical series.

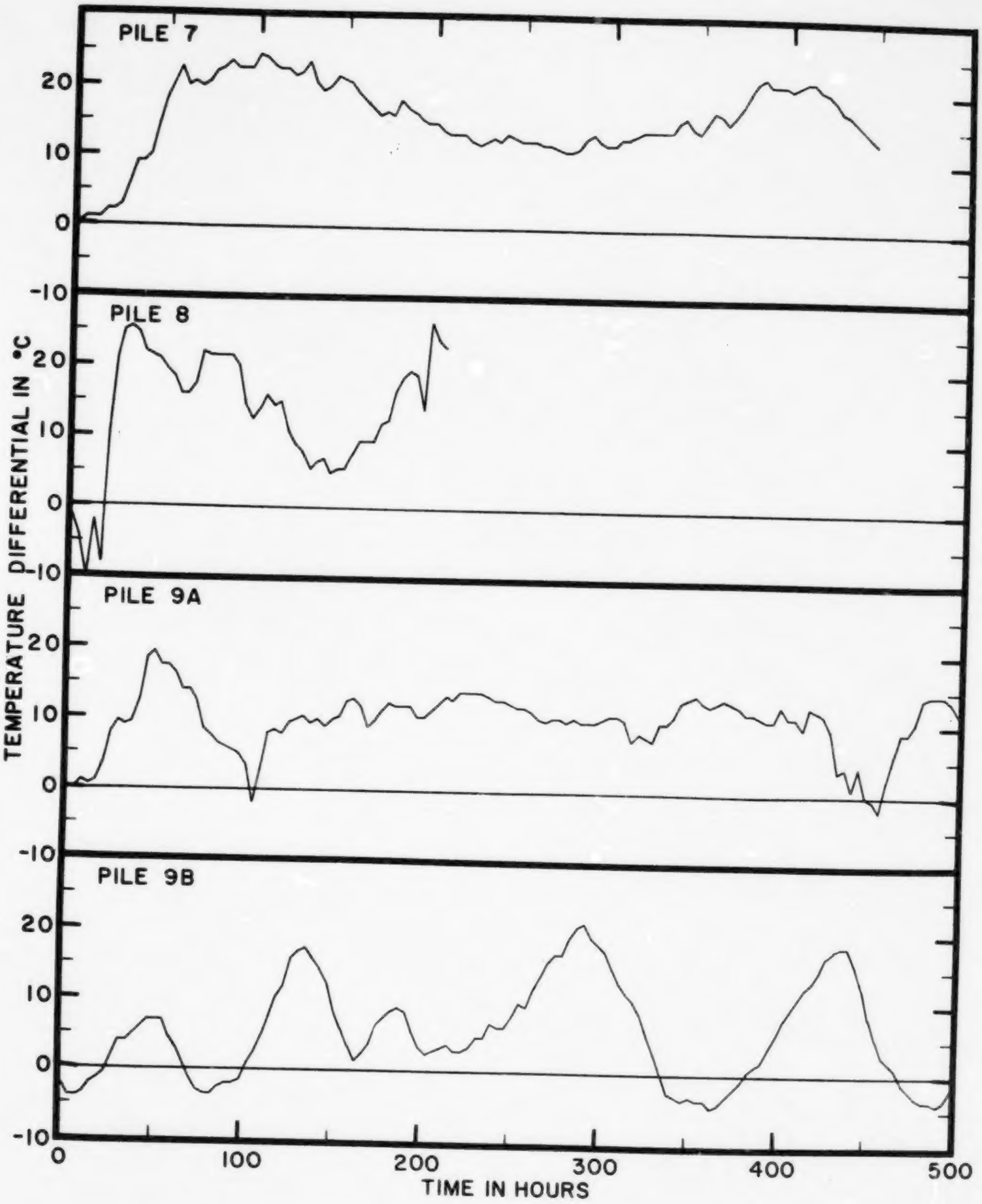

Figure 30. Temperature differential over a 0.9m vertical distance. The values plotted are as follows: pile 7, position 16-position 6; pile 8, position 18-position 6; pile 9A, position 18-position 6; pile 9B, position 2-position 14.

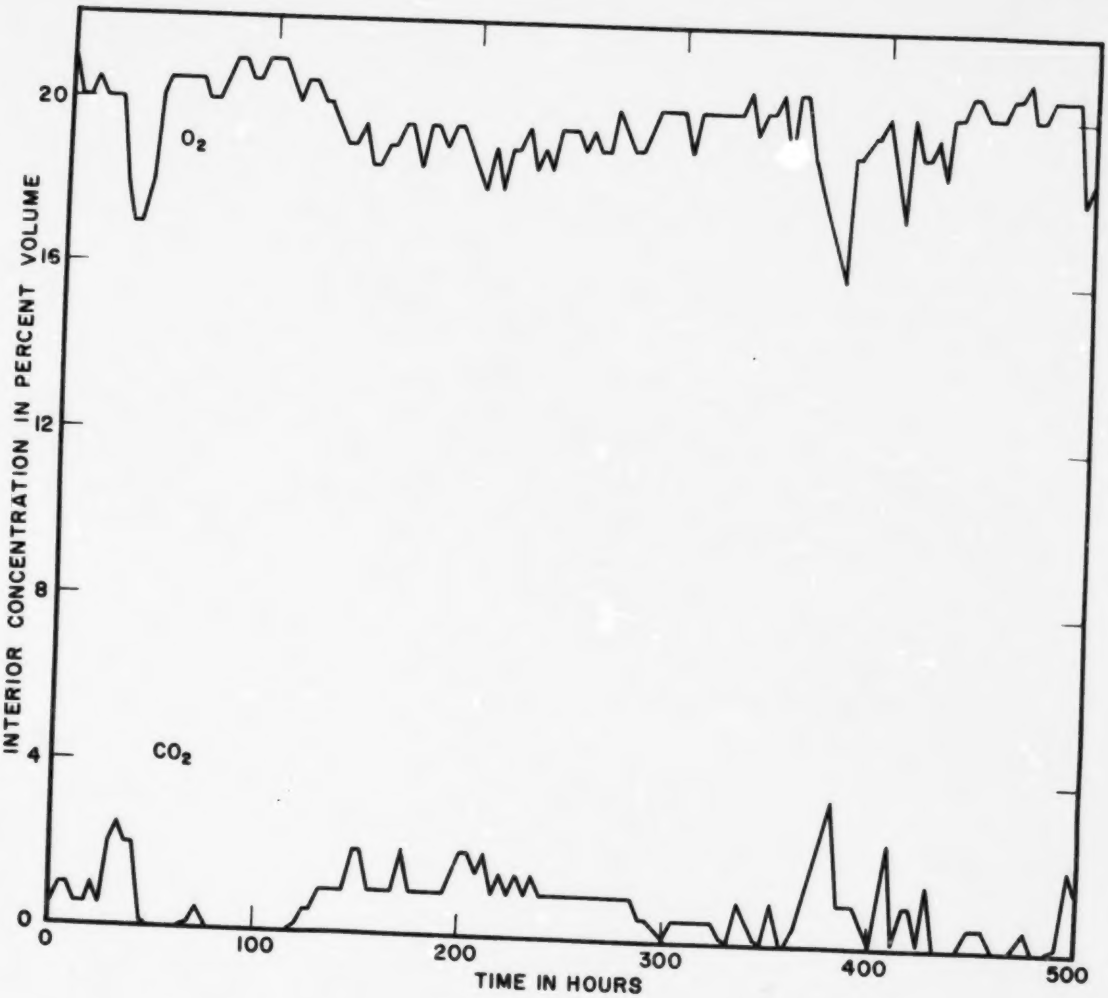

Figure 31. Pile 9A, concentrations of O_2 (upper curve) and CO_2 (lower curve). The gas sampling probe was adjacent to position 7.

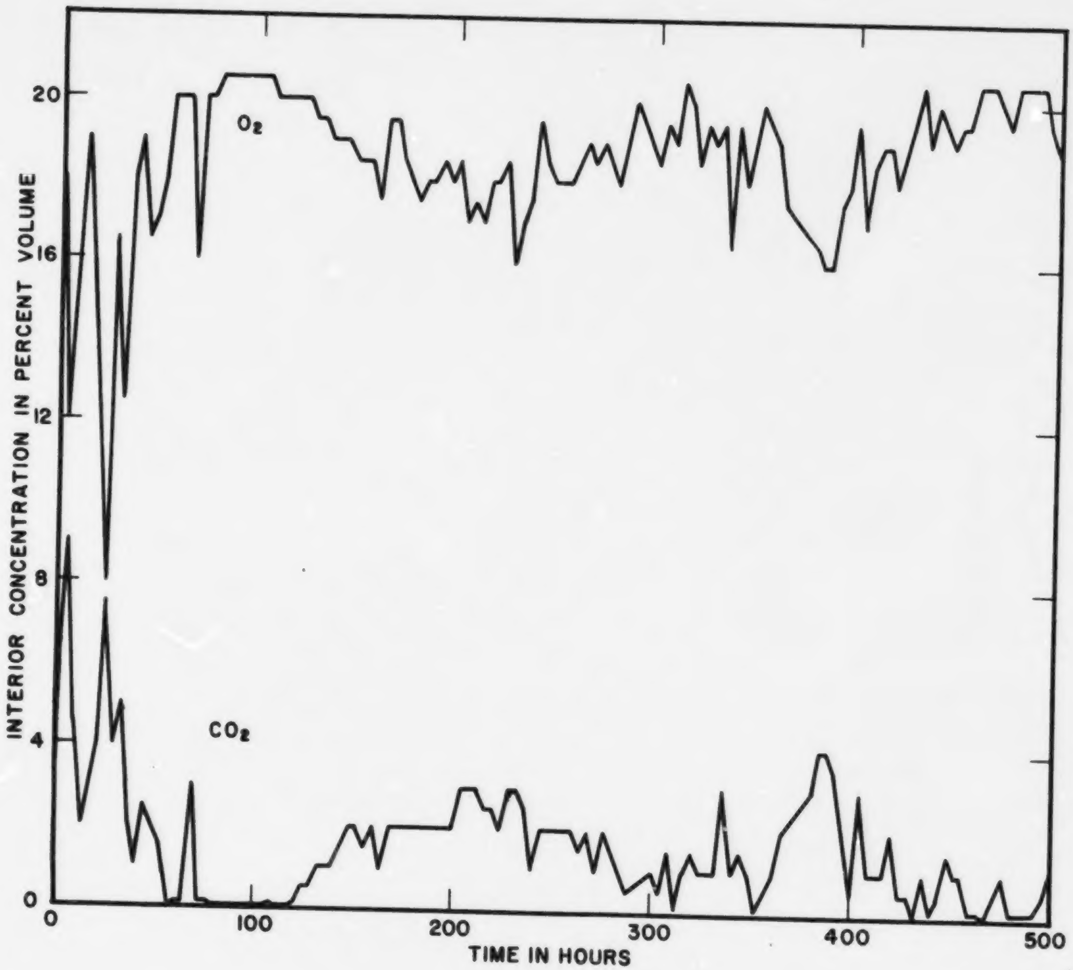

Figure 32. Pile 9A, concentrations of 0_2 (upper curve) and $C0_2$ (lower curve). The gas sampling probe was adjacent to position 16.

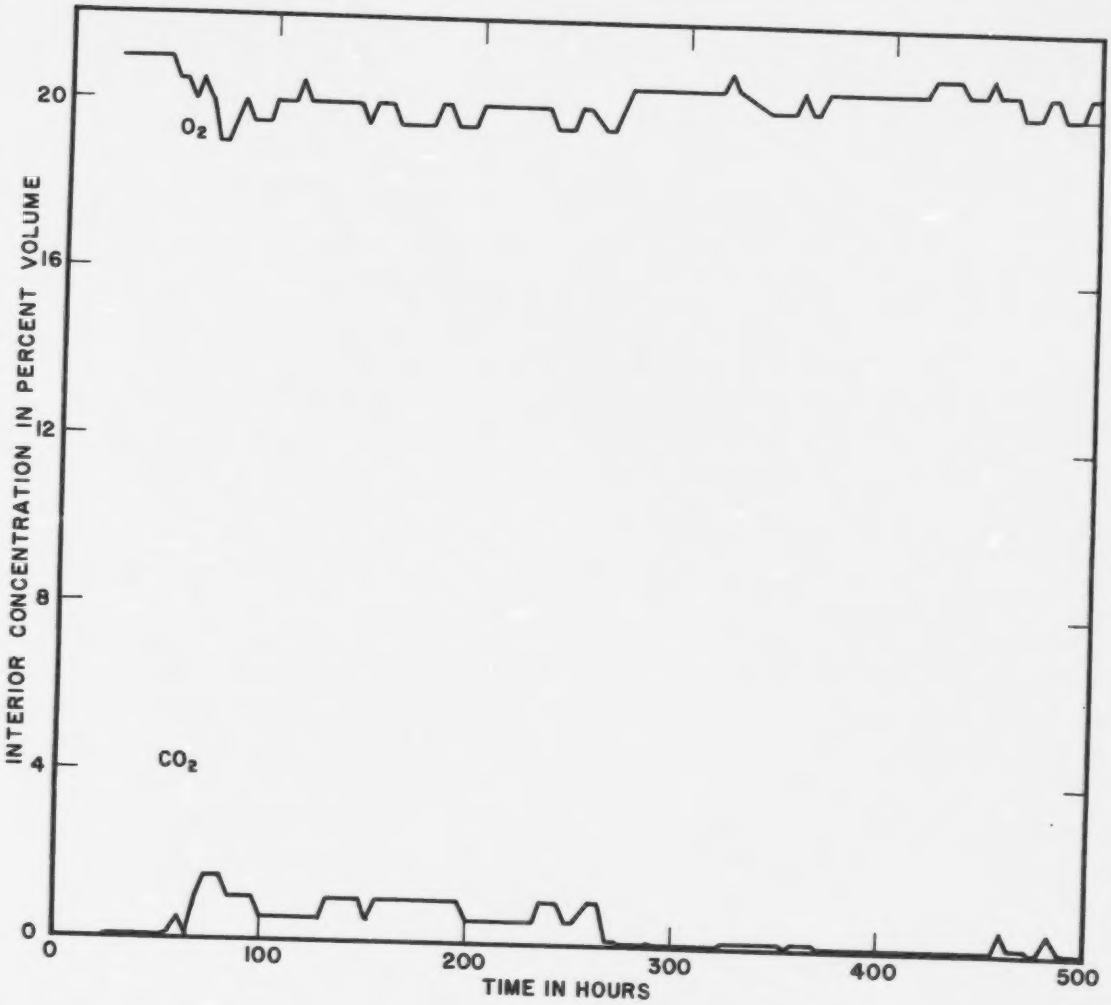

Figure 33. Pile 9B, concentrations of O_2 (upper curve) and CO_2 (lower curve). The gas sampling probe was adjacent to position 7.

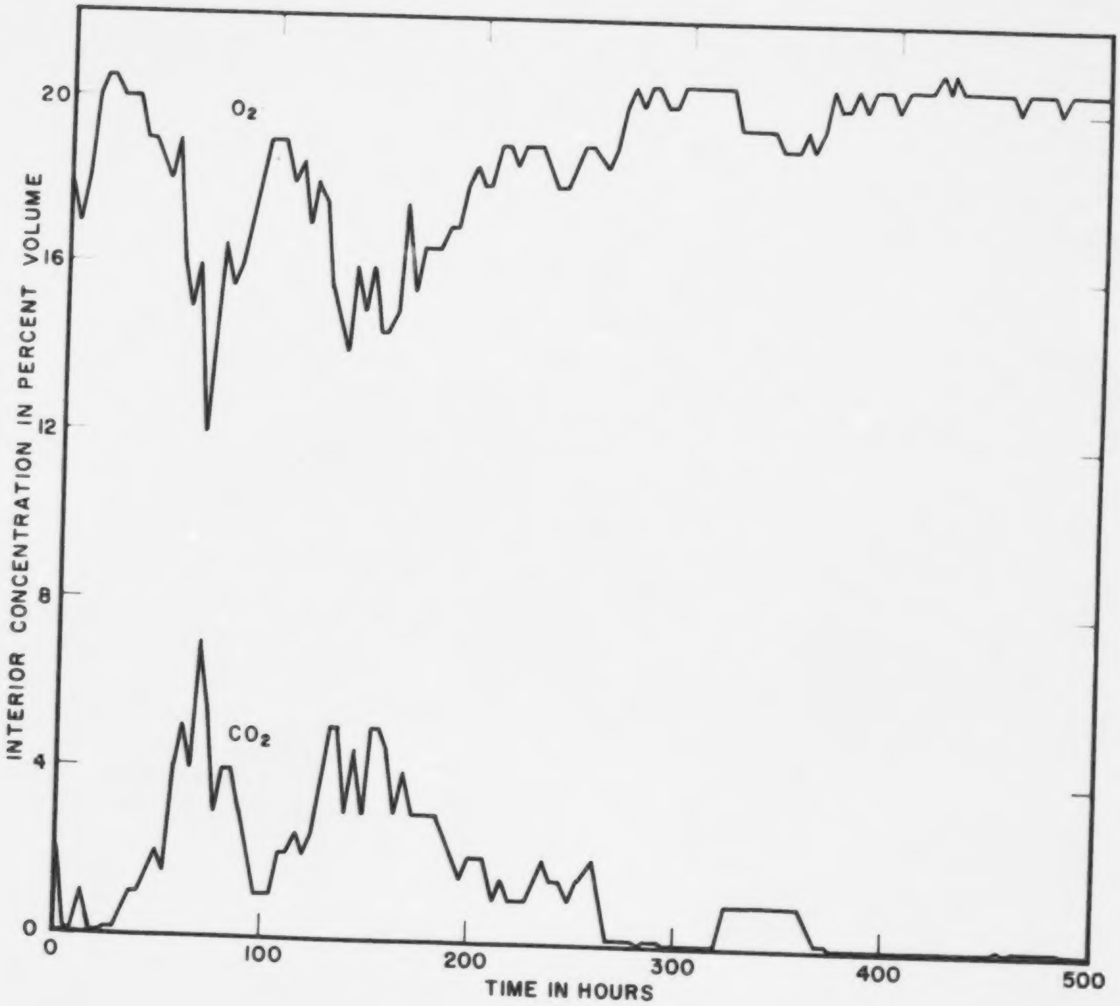

Figure 34. Pile 9B, concentrations of O_2 (upper curve) and CO_2 (lower curve). The gas sampling probe was adjacent to position 14.

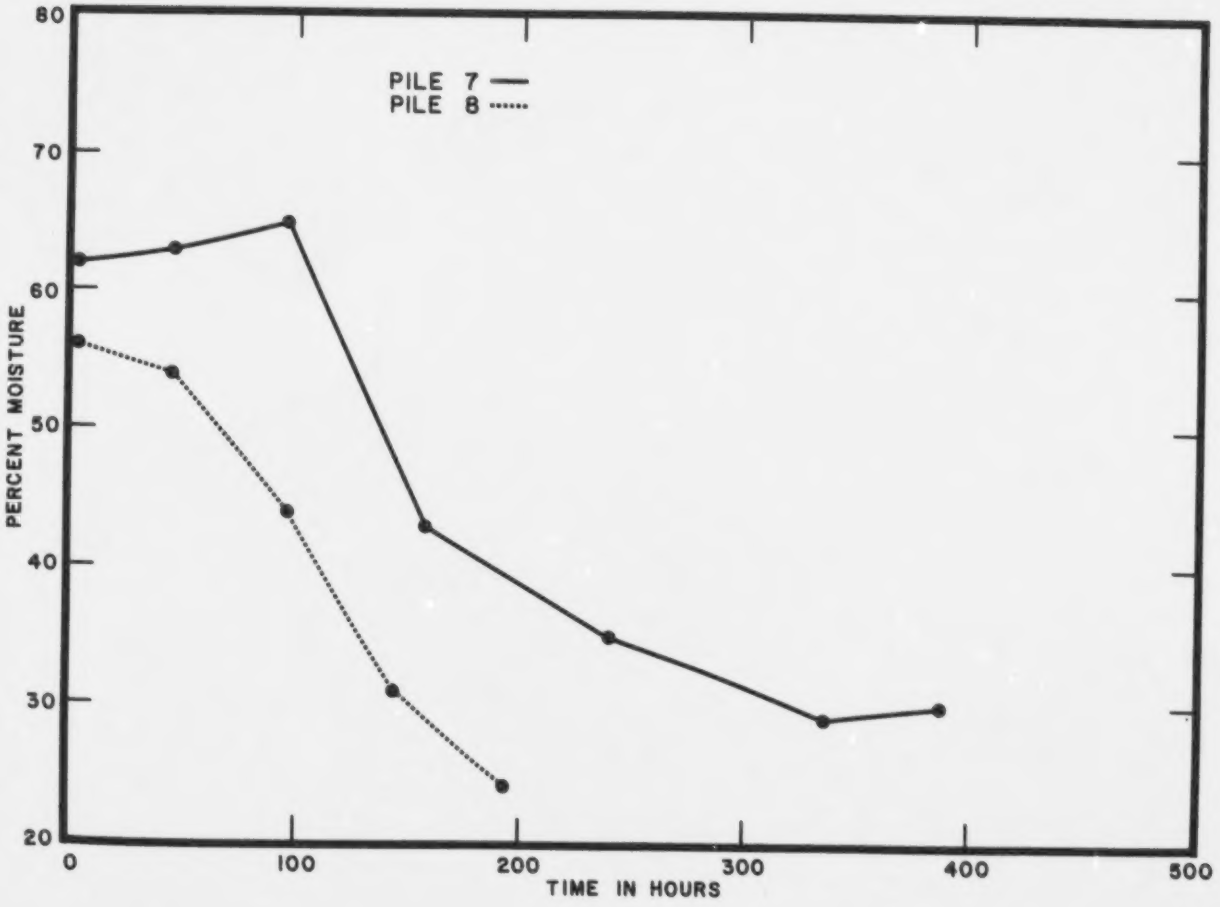

Figure 35. Piles 7 and 8, moisture content. Samples taken from central interior locations. The data refers to "whole samples" (includes woodchips).

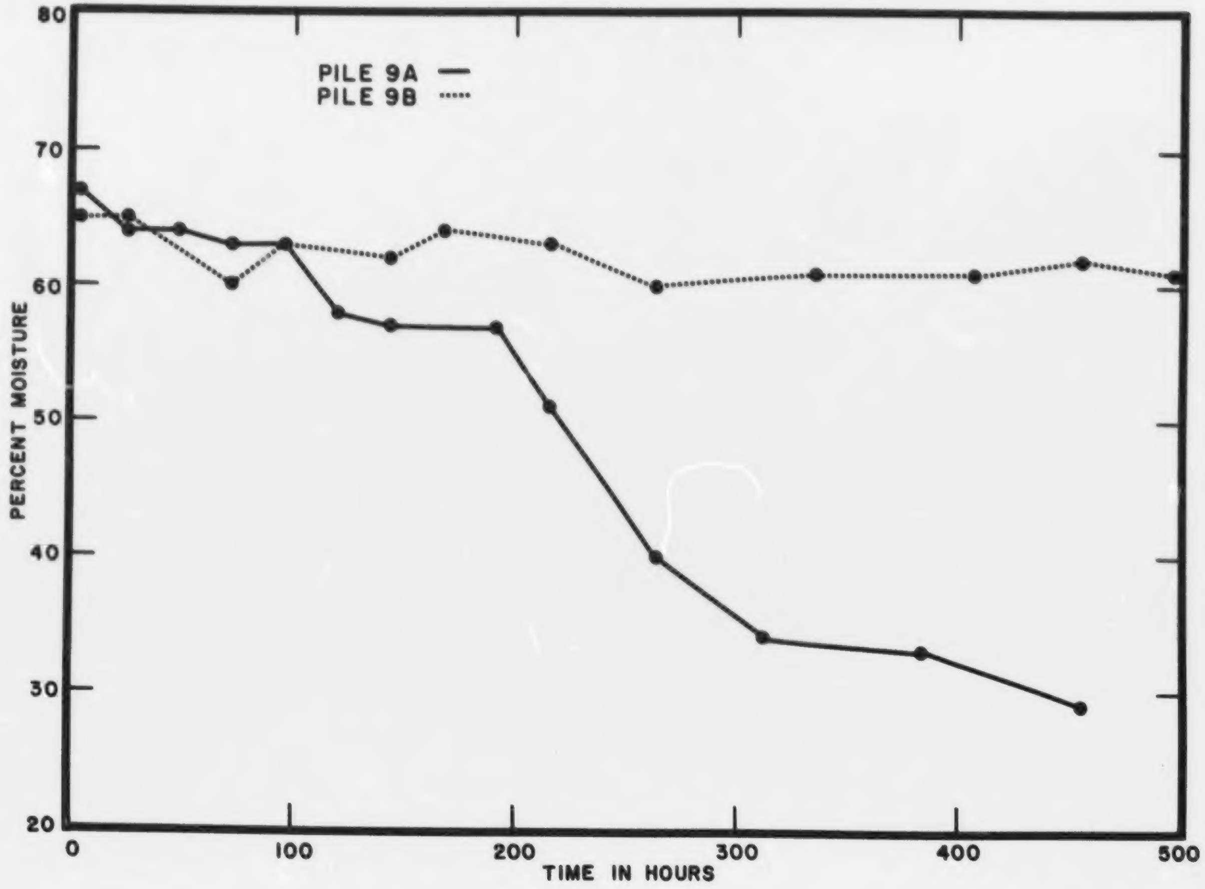

Figure 36. Piles 9A and 9B, moisture content. Samples taken from central interior locations. The data refers to "whole samples" (includes woodchips).

ed rapidly. The Beltsville pile (9B) dried only slightly, with the terminal value being 61%.

pH

The pH data are given in Figures 37 and 38. The pH increase of pile 9A was less than that of piles 7 and 8 and comparable to previously reported piles (2). Pile 9B was atypical in that the pH decreased.

Leachate

Liquid was last seen issuing from pile 9A on day 3, and from pile 9B on day 17.

REPRESENTATIVENESS OF PILE 9B

Piles 7, 8 and 9A represented the Rutgers strategy, whereas only pile 9B was constructed and managed according to the Beltsville prescription. The representativeness of pile 9B was assessed by comparing its behavior with that of Beltsville-type piles reported by others (9, 38-39). The analysis (see Appendix A-4) demonstrates i. a consistency of behavior among piles managed according to the Beltsville prescription, ii. a consistency of behavior among piles managed according to the Rutgers strategy, iii. dissimilar behavior between the two groups of piles. It is concluded that pile 9B adequately represented the Beltsville Process.

GENERALIZED COMPARISON OF THE STRATEGIES

The objective of the Rutgers process control strategy is to maximize the rate of microbial decomposition. Operationally, this translates into the optimization of temperature via controlled ventilation. For a brief period at the outset of processing (ca., 1 day) the purpose of ventilation is to promote a rapid temperature ascent. Thus, the need to provide O_2 for heat generation, through aerobic respiration, temporarily conflicts with the need to minimize heat removal. The compromise is to actuate the blower, by timer, on a schedule to provide an adequate O_2 level (ca. 5%).

When the temperature reaches a preset level (T_{set}) assigned to a controller and sensed via a thermistor in the pile, the purpose of ventilation changes to that of matching heat removal to heat output, such that pile temperature is poised at a biologically favorable level (<60°C). This is achieved automatically through establishment of an interaction between pile and blower, via the feedback of a temperature signal to the controller. With the onset of temperature feedback control the conflict described above disappears, as the needs of O_2 supply and heat removal now coincide. The period of feedback control ends at some indeterminate time (typically 8-15 days), when the loss of heat independent of ventilation by "demand" starts to exceed heat generation.

The required ventilation capacity (e.g., blower horsepower) is defined by the peak demand for heat removal, which is primarily a function of the abundance of readily metabolizable substrate in the waste. The forced-pressure mode of ventilation is preferred for its greater efficien-

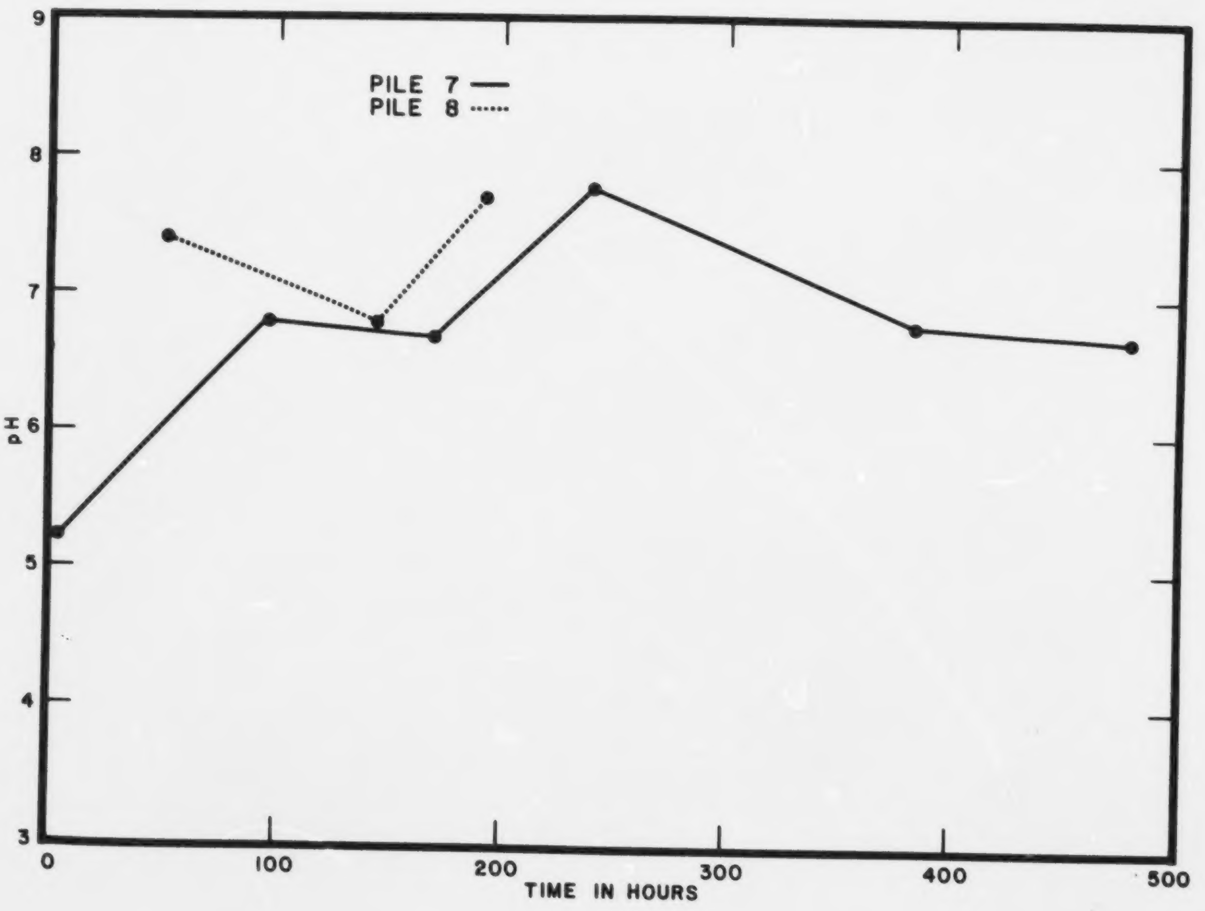

Figure 37. Piles 7 and 8, pH. Samples taken from central interior locations.

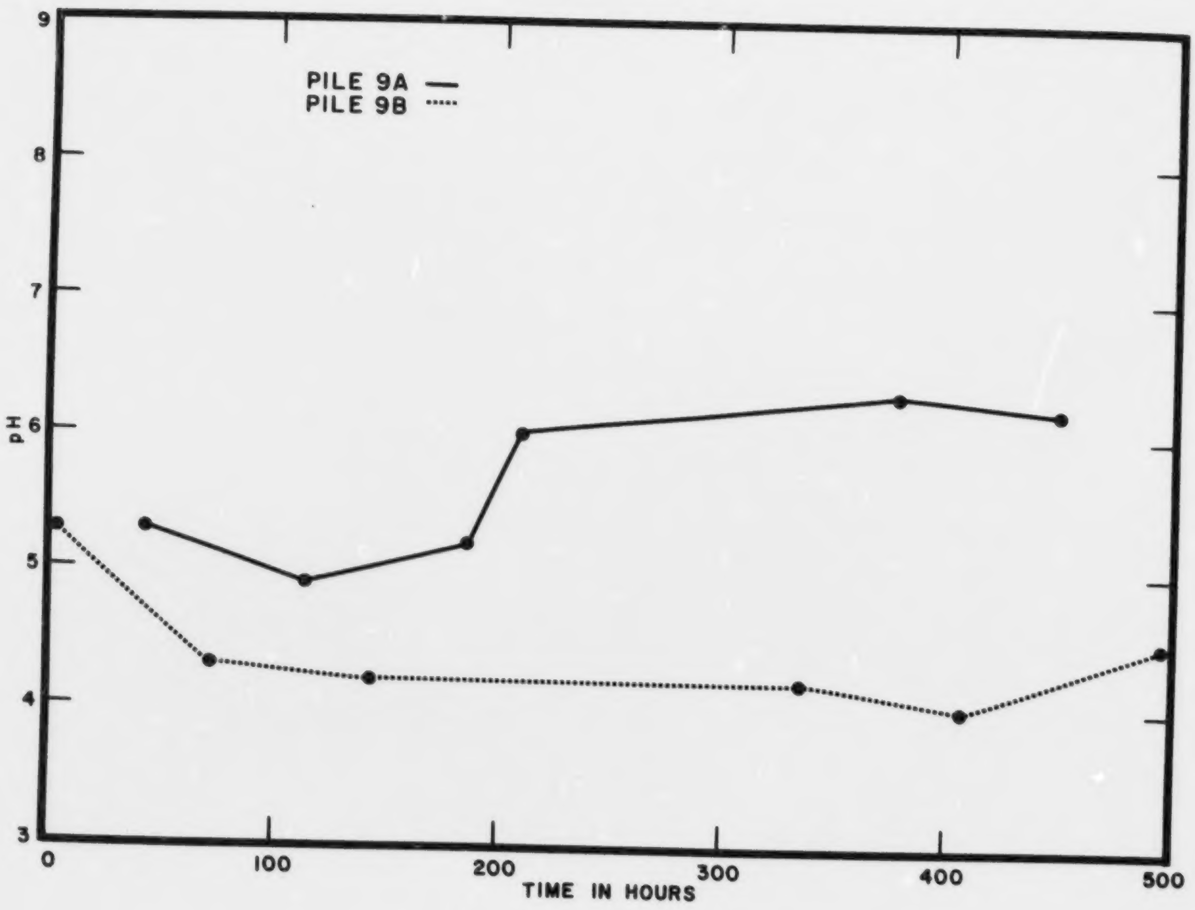

Figure 38. Piles 9A and 9B, pH. Samples taken from central interior locations.

cy in removing heat and water vapor (7).

In the Beltsville Process the stated purpose of ventilation is to maintain O_2 at a level of from 5% to 15% (9). This is accomplished (8) through use of a timer to schedule blower actuation and deactuation. Usually the blower is operated 20% of the time, but this percentage may be varied manually based on O_2 level. Pile temperature typically peaks at 80°C within a few days and changes little for the remainder of this operational stage, which is fixed at 21 days. A subsequent period of informal curing typically lasts several months. Blower size is standardized at 1/3 hp per 45 wet tonnes of sludge cakes, regardless of the type of sludge (e.g. raw, waste activated, anaerobically digested).

UNIFIED INTERPRETATION OF EVENTS INDUCED BY THE TWO STRATEGIES

This interpretation is based on the plug flow of air through a composting matrix, and the interaction between heat generation and temperature. We start by considering two roles of ventilation: supplying O_2 and removing heat. In turn this leads to a consideration of water removal. Removal of CO_2 can be neglected for the present purposes.

The O_2 (% vol/vol) at any given point along the airflow pathway represents the balance between the rate of microbial O_2 uptake and the rate of resupply through ventilation. Although the two control strategies result in similar O_2 contents, this reflects dissimilar rates of uptake and resupply.

In the Rutgers strategy the sequence of control-related events is: O_2 is consumed through microbial activity, which generates heat; the temperature increases, resulting in a signal actuating the blower; ventilation removes heat and resupplies O_2; the temperature decreases, deactuating the blower. The cycle is repeated until the period of temperature-feedback control terminates, reflecting a low rate of heat generation. In a direct sense the response of the blower is time-variable according to the rate of heat generation, as expressed through temperature. Indirectly, however, the response is time-variable according to the rate of O_2 uptake, in that O_2 uptake and heat generation both result from organic matter decomposition. The rates of O_2 uptake and heat generation are therefore directly proportional. Since the response threshold (T_{set}) is selected to maximize heat generation and O_2 uptake, intrinsic to the Rutgers strategy is a high rate of O_2 uptake matched by a high rate of O_2 resupply. The result is a well-oxygenated pile.

In the Beltsville process the sequence is: slight ventilation removes heat and resupplies O_2 in slight amounts; the temperature ascends to a level that suppress O_2 uptake and other manifestations of microbial activity. The rate of resupply of O_2, though low, suffices to maintain an oxygenated condition because of the slight metabolic activity. Thus, the stated objective of maintaining O_2 at a level of 5% to 15% (9) is met by suppressing microbial metabolism (waste decomposition) through operation at biologically harsh temperatures.

Ventilation should now be considered from the vantage point of heat and water removal. Removal through radiation and conduction is insignificant or minor (4), and these mechanisms may be neglected for the present purposes. Heat is transferred from the solid phase (composting matrix) to the gaseous phase (flowing airstream) through the mechanisms of convection and vaporization of water. Vaporization is the dominant mechanism, removing approximately nine-fold more heat than convection (2). For the transfer to occur an enthalpy (heat content) differential must exist between the phases. Because the matrix is the site of heat generation, its enthalpy is elevated relative to the air. As the air flows through the matrix it progressively accumulates heat, decreasing the differential and thus the potential for transfer. This set of circumstances induces the progressive storage of heat in the matrix material along the axis of airflow, resulting in the establishment of a positive temperature gradient in the direction of airflow. The temperature gradient, in turn, maintains an enthalpy differential between the phases.

Based on the relationship between the enthalpy differential and the temperature gradient, drying in the vertical dimension is expected to be relatively uniform. This is because the flowing air continuously approaches a saturated condition yet, provided that the adjacent matrix remains a site of heat generation, does not reach saturation. Consistent with this expectation, repeated informal observation indicated uniform drying.

In contrast, ventilation of a metabolically inert mass (no heat generation) causes vaporization only insofar as the inlet air is unsaturated. This is the subject of Section 8.

Meanwhile, it is sufficient to note that in the metabolically inert system a discrete cooling-drying front (evaporative cooling) is expected to migrate gradually through the pile, and that this was observed in a ventilated pile of well-curved, essentially inert, compost. Relating the data from the pile of compost to those from the Rutgers composting piles, an estimated 95.5% of the composting-associated drying is attributable to heat generation and the remainder (4.5%) to unsaturation of the inlet air. Similarly, a theoretical calculation attributes 95% to 98.2% of the composting associated drying to metabolic heat generation (Appendix A-5).

Thus, drying during composting is linked to organic matter decomposition, in that the vaporization is driven almost exclusively by heat generation. Since decomposition of putrescible material is the primary goal of waste treatment, we earlier suggested (2-4), that the course of drying can serve as a specific, objective, sensitive, and convenient indicator of process performance. In this application the moisture content test is more sensitive than the volatile solids test (Appendix A-6). Figures 35 and 36 thus serve to represent the comparative performance of the two static-pile composting processes.

DISCUSSION

These observations provide a coherent framework for composting process control based on interactions among microbial heat generation, temperature, vaporization, and ventilation. This is given below.

i. The composting microbial ecosystem tends strongly to self-limit via excessive accumulation of metabolically generated heat, leading to inhibitively high temperature. The threshold to significant inhibition is approximately 55°-60°C, and its severity increases sharply at higher temperatures. Unless controlled through deliberate heat removal, composting masses typically peak at 80°C, at which point the rate of decomposition is extremely low.

ii. This self-limiting tendency must be countered if decomposition is to be fostered. Consequently, the central problem in the design and control of composting facilities is heat removal in reference to a 60°C operational ceiling.

iii. A practical means of removing heat from the composting mass is through ventilation. The main ventilation-associated mechanism of heat removal (ca. 90%) is the vaporization of water. Ventilation also supplies O_2 for aerobic decomposition (main source of heat).

iv. The forced pressure-mode of ventilation removes heat more efficently than the vacuum-induced mode.

v. During composting the rate of heat generation is time-variable. Hence, to maintain a given temperature this must be matched by correspondingly time-variable heat removal. Implementation is through temperature feedback actuation of a blower, using standard control equipment. Composting mass and blower thereby interact, to seek an assigned set-point temperature.

vi. To achieve the desired operational ceiling of 60°C, it might be necessary to assign a lower set-point (e.g. 45°C).

vii. The blower capacity (head and volume) must suffice to meet peak demand for ventilation. A strong waste (e.g. raw sewage sludge) demands more ventilation than a weak one (e.g. digested sludge).

viii. A temperature gradient is established along the axis of airflow. This imposes a height limitation, above which a high rate of decompostion is not obtainable. With the sludge tested herein, the limitation was approximately 2 meters. Drying is relatively uniform along this axis of airflow.

ix. Managed thusly, decompostion and drying are related in that the following chain of causation is established: decomposition generates heat; the heat vaporizes water; the vaporization causes drying. Production of metabolic water replenishes only ca. 10% of the water removed.

x. A consequence of this control strategy is that the composting mass is well-oxygenated (typical O_2 level, 17% v/v). This is because approximately 9x more air is needed to remove heat than to supply O_2 for aerobic respiration.

This framework results from a comparative analysis of two fundamentally different approaches to the management of the composting-microbial ecosystem. These are represented by the Rutgers strategy and the strategy embodied in the Beltsville Process. It may be doubted whether a different analytical point of departure could lead to a coherent framework.

The study material was sewage sludge, and the configuration that of unenclosed static pile. The derived principles are nonetheless relevant to other materials and configurations. The static pile configuration, however, is structurally and operationally simple, and is therefore preferred.

SECTION 4

SEQUENCE OF LIMITATIONS INDUCED BY CONTROL STRATEGY

INTRODUCTION

The Rutgers strategy is to maximize the rate of decomposition via heat removal in reference to temperature. Since the main heat removal mechanism is the vaporization of water, a strong drying tendency is induced. Consequently, the prevention of inhibitively high temperature promotes dryness, possibly to an inhibitive extent.

Conversely, the Beltsville process focuses on the maintenance of a minimal level of interstitial O_2. This leads, by default, to inhibitively high temperatures and the retention of water.

The present Section concerns dryness as a limiting factor. The experimental observations support a general discussion of the sequence of limitations, and its practical implications in sludge management.

MATERIALS AND METHODS SPECIFIC TO SECTION 4

These observations concern one pile of the sludge-woodchip mixture (Figure 39), managed according to the Rutgers strategy. Departures from the Materials and Methods described in Section 3 are that the sludge-woodchip ratio was 1 tonne sludge per $1.5m^3$ woodchips (1 ton per 1.8 yd^3); the infrared analyzer for CO_2 determination was a Beckman Model 315; the material tested for moisture content had been passed through a 0.64m (¼ in.) sieve (ASTM E-11 specification).

The trial period was 10 May to 25 June, 1979. Ambient air temperatures during this period were (°C): mean of the daily highs, 24.6; mean of the daily lows, 14.5; mean of the daily means, 19.6; range of the daily highs and lows 9 to 31. Rainfall amounted to 26 cm in 20 occurrences.

The pile is represented by Figure 39. On four occasions (see arrows, Figure 40) water was added to the central portion of the pile. through various procedures. Occasion 1: approximately 445L (120 gallons) of water was pumped through a gas sampling probe positioned variously in the central portion of the pile. Occasion 2: four 176L (20 gallon) containers filled with water were carried to the top of the pile and emptied. Occasion 3: water was applied to the pile surface with a fire hose, at a low rate, for approximately 90 minutes Occasion 4: water was applied to the pile surface with a fire hose, at a moderate rate, for approximately 10 minutes.

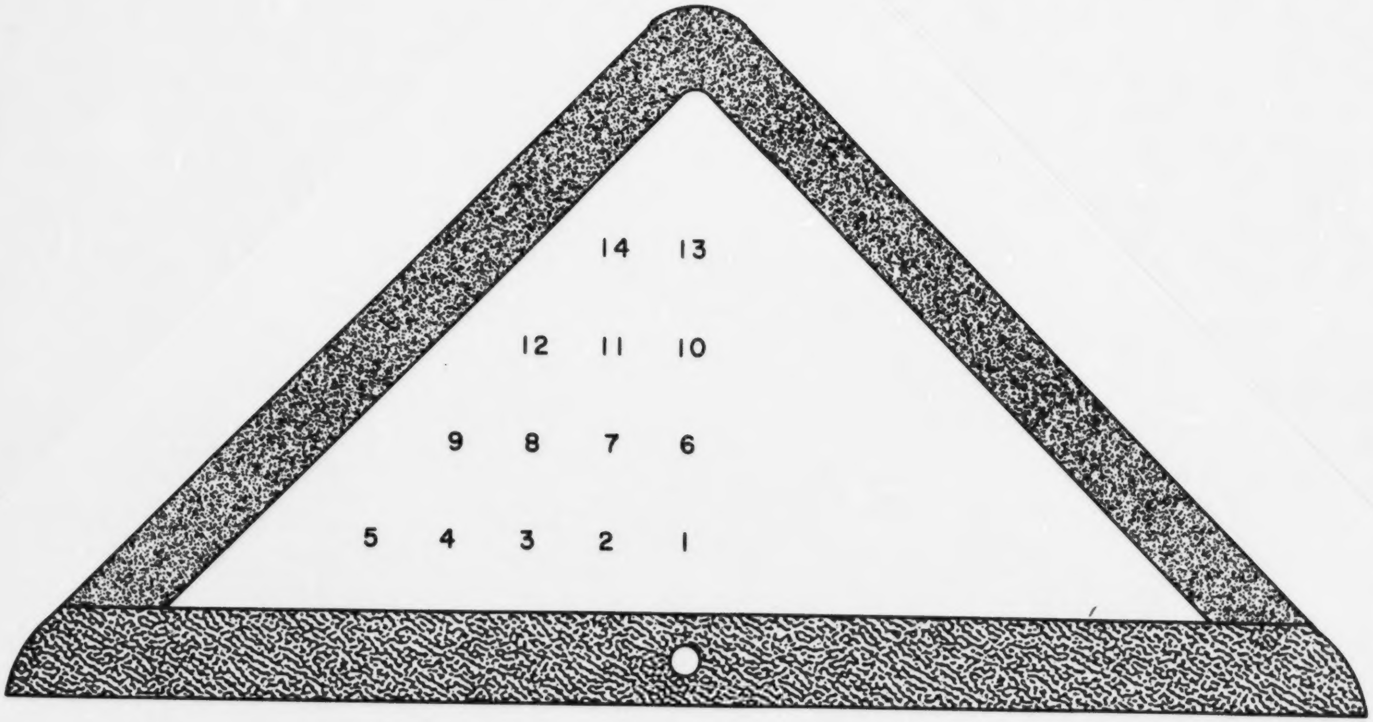

Figure 39. Pile 4A, cross-sectional representation: textured area, woodchip cover and base; clear area, sludge-woodchip mixture; circle, perforated flexhose. The numbers indicate monitoring and control positions: thermocouples, positions 1 through 14; control thermistor, position 1. The blower was operated in the forced-pressure mode. (This pile was designated 4A in reference 4, and A in reference 2.)

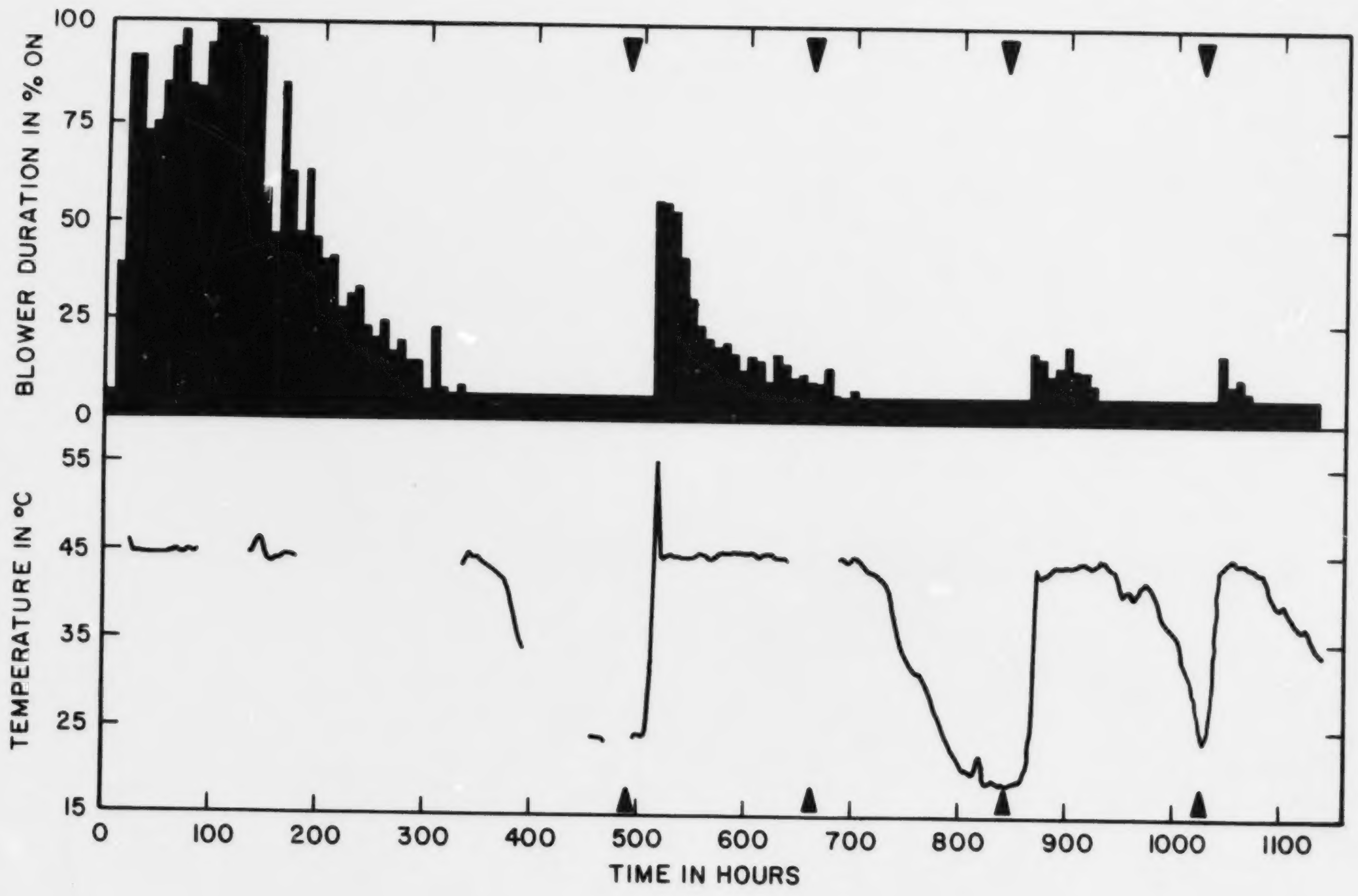

Figure 40. Pile 4A, blower operation, and temperature at the control thermistor. The baseline represents operation as scheduled by timer, and the area above the baseline represents operation through the temperature-feedback control system. The time of water addition is indicated by arrows.

RESULTS

Hour Zero to Hr 490

Blower operation first exceeded that schedule by timer at hr 12, indicating that the controller had responded to a thermistor temperature of >45°C (Figure 40). This marks the start of the period of temperature-feedback control. Blower operation was nearly continuous from hr 80 to 150. Feedback control terminated at hr 352, at which time blower operation reverted to that scheduled by timer (7% of the time).

Based on 1020 observations during the period of feedback control, the median pile temperature was 48°C, and the range was 25°C to 63°C. Temperatures in excess of 60°C accounted for 1.8% of these data points. The temperature at the thermistor control position is shown in Figure 40.

The level of CO_2 peaked at 14% just prior to the start of the period of feedback control. Thereafter, CO_2 generally varied between 2% and 4%.

The starting moisture content of 76% decreased to 22% in 15 days (Figure 41). This refers to sieved material (woodchips removed).

Hour 490 to Hr 1140

Immediately prior to the first water addition the temperature at the thermistor position had declined to well below the set point value (24°C observed vs. 45°C set point), and blower operation was solely as scheduled by timer. At this time the moisture content was 22%.

Water was added, as described above, to the part of the pile containing the control and monitoring devices (see Figure 39). The material absorbed water slowly and non-uniformly, therefore representative samples for the determination of moisture content were not obtainable in this part of the study.

Approximately ten hours after the first water addition the temperature re-ascended, initiating a second period of feedback control. Before the termination of this period the second water addition was made. Shortly thereafter feedback control ceased, and blower operation by timer-schedule resumed. The third and fourth water additions initiated independent, successively weaker, periods of feedback control.

The comparative intensity of the successive periods of feedback control may be judged on the basis of the amount of blower operation time. Baseline blower operation, as scheduled by timer, is included in this comparison. Setting blower operation during the original period (hr 10 to hr 348) equal to 100, the other values are: hr 519 to hr 69, 20.2; hr 872 to hr 946, 5.9; hr 1044 to hr 1070, 1.8.

During the part of the trial from hr 490 to hr 1140, rainfall amounted to 10.8 cm in 8 occurrences. The heaviest rainstorm,

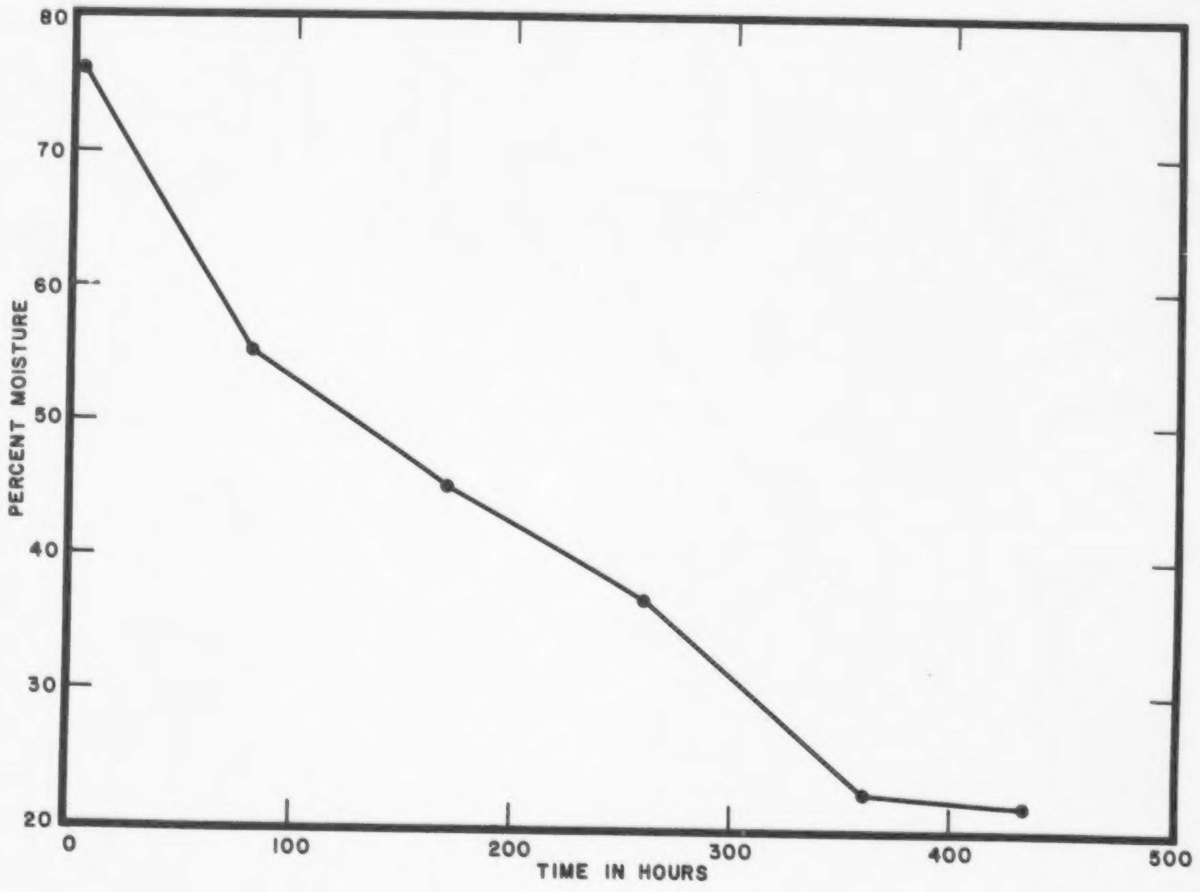

Figure 41. Pile 4A, moisture content. Samples taken from central interior locations.

depositing 6.2 cm, started on hr 735 and ended on hr 755. This storm occurred between periods of temperature-feedback control (see Figure 40). The rainfall wetted the pile only superficially, and did not revive blower demand.

DISCUSSION

Four factors can come to limit microbial activity in a composting mass. These are: O_2 depletion; development of excessively high temperature; water depletion; substrate depletion. Except for substrate, whether a particular limitation comes into play or is bypassed depends on the means of ventilation employed and whether water is added (Figure 42).

The sequence is discussed in reference to specific examples. Oxygen depletion is exemplified in the composting of leaves in static piles without mechanical ventilation, as reported elsewhere (40). A summary of the pertinent observations follows.

Soon after assembling leaves into a pile of substantial size, e.g., L x W x H = 7.6x3.1x1.8m (25x10x6 ft), the interior portion of the pile became O_2-deficient (defined as O_2 not detectable or barely detectable). The O_2-deficient portion comprised roughly half the total pile volume. The outer portion (roughly half the volume) remained well-oxygenated. The maximum temperature throughout the pile rarely exceeded 60°C, presumably reflecting the slight generation of heat fermentatively compared to O_2-based metabolism. Over the ten month observation period the pile shrunk to approximately half its original volume. The relative proportions of O_2-deficient and oxygenated volumes remained approximately equal.

At termination the pile was disassembled for examination. The material in the oxygenated zone was damp and appeared to be humified, whereas in the central core the material was wet, gave off an odor of putrefaction, and retained evidence of the original leaf structure. Thus, overall the leaves had not yet received adequate treatment.

Nonetheless, it was concluded that satisfactory composting of leaves is possible without mechanical ventilation (or agitation). For this type of waste the need is to insure that the material in the innermost core becomes oxygenated within the processing time available, in that this signifies that all of the material has undergone thorough decomposition. Provided that the leaves are moist at the outset, adequate decomposition throughout occurs over winter.

An inadequate ventilation system, in terms of blower capacity and/or control system, leads to inhibitively high temperature, whereas an adequate system leads to dryness and/or substrate depletion. These circumstances are represented by the Beltsville Process and the Rutgers control strategy, respectively, as was developed earlier.

The practical implications of this sequence are illustrated through three hypothetical cases. The first concerns a "dirty sludge," contaminated with heavy metals and/or non-biodegradable industrial

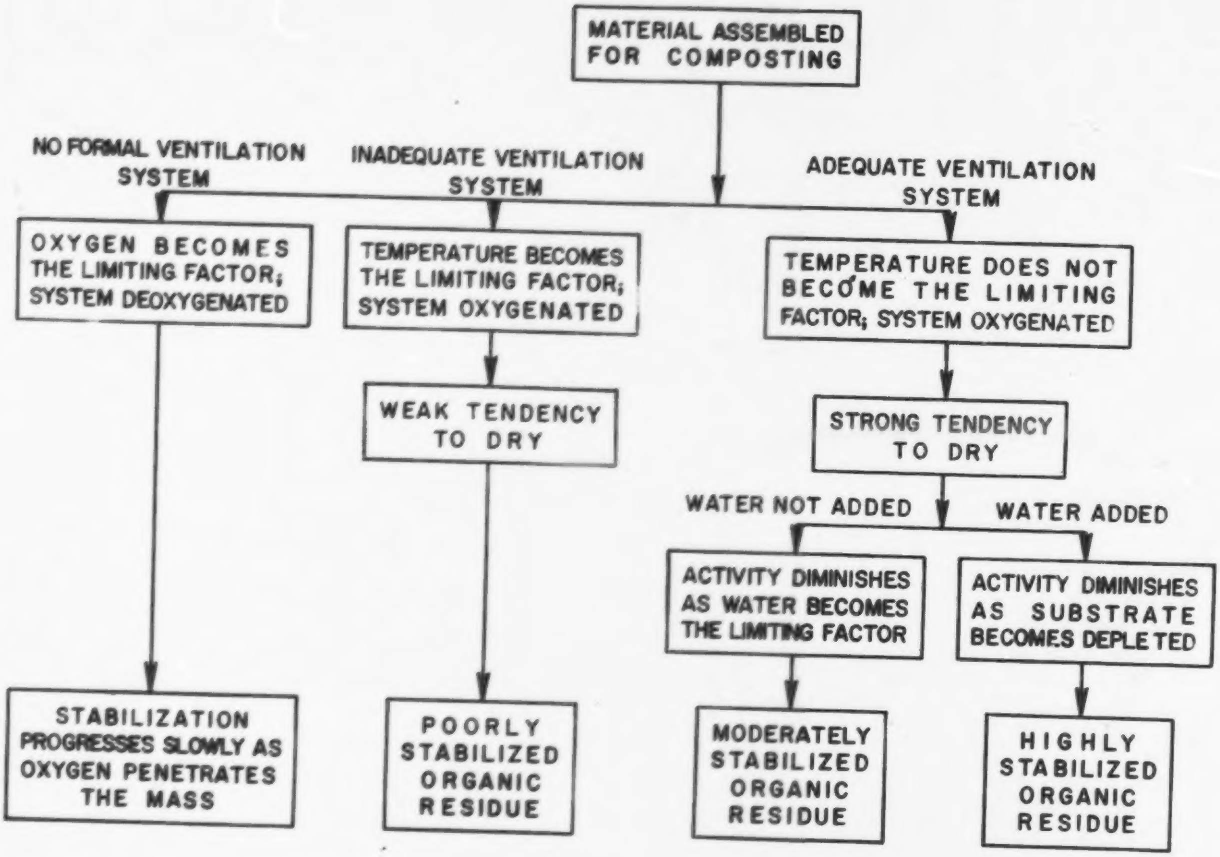
MATERIAL ASSEMBLED FOR COMPOSTING
NO FORMAL VENTILATION SYSTEM
INADEQUATE VENTILATION SYSTEM
ADEQUATE VENTILATION SYSTEM
OXYGEN BECOMES THE LIMITING FACTOR; SYSTEM DEOXYGENATED
TEMPERATURE BECOMES THE LIMITING FACTOR; SYSTEM OXYGENATED
TEMPERATURE DOES NOT BECOME THE LIMITING FACTOR; SYSTEM OXYGENATED
WEAK TENDENCY TO DRY
STRONG TENDENCY TO DRY
WATER NOT ADDED
WATER ADDED
ACTIVITY DIMINISHES AS WATER BECOMES THE LIMITING FACTOR
ACTIVITY DIMINISHES AS SUBSTRATE BECOMES DEPLETED
STABILIZATION PROGRESSES SLOWLY AS OXYGEN PENETRATES THE MASS
POORLY STABILIZED ORGANIC RESIDUE
MODERATELY STABILIZED ORGANIC RESIDUE
HIGHLY STABILIZED ORGANIC RESIDUE

Figure 42. Reprinted by permission from BIO/TECHNOLOGY, Vol. 1, No. 4, pp. 347-353. Copyright © 1983. Nature Publishing Co. Limitations to biological activity induced by different management strategies.

chemicals. Such a sludge should not be considered as a feedstock for compost production, yet composting might be the treatment process of choice. The process residue might be suitable as a landfill cover material, or as a low grade solid fuel. This residue is desireable as a fuel, compared to the uncomposted sludge cake (Appendix B).

The second and third hypothetical cases involve a "clean sludge," which affords a wider range of opportunities for ultimate disposal via resource recovery. Consider the production of a "rough" compost for restricted bulk application to soil. This product must be aesthetically acceptable and remain so after application to soil, hence it should be moderately well stabilized. More extensive stabilization than required to meet this need is undesireable as it adds to processing costs and results in a loss of agronomically valuable nitrogen and organic matter. Production of a "rough" compost calls for a relatively high initial moisture content (consistent with reliable process "start-up"), to prolong the period of microbial action prior to dryness.

Finally, production of a highly stabilized compost for unrestricted distribution calls for more extensive biological decomposition. This might be accomplished in-place, as an extension of a high rate stage, by adding water to prevent premature dryness. In this manner the high rate stage would gradually pass to an in-place curing stage. Alternatively, the material might be permitted to become dry in the high rate stage and then moved, and remoistened, for curing. Other unit process flow schemes can be envisioned.

SECTION 5

RUTGERS STRATEGY: REPLACEMENT OF WOODCHIPS WITH RECYCLED COMPOST AS THE BULKING AGENT

INTRODUCTION

Composting requires gas exchange to remove heat and water vapor and to supply O_2. Mechanical agitation can provide the needed exchange only intermittently, and at high energy cost. Thus, agitation does not lend itself to rate maximization through controlled heat removal, and its main role in composting is to mix and abrade the material. Ventilation by blower affords the only practical approach to rate maximization, but this imposes a requirement for porosity to permit the passage of air. Since sludge cake by itself lacks porosity, it is commonly mixed with a "bulking agent" having this property.

The usual bulking agent, woodchips, has serious drawbacks. In routine Beltsville-type operations, the purchase of woodchips and associated operations (storage, translocation, mixing, screening) represent perhaps one-third of the overall costs (41). Furthermore, woodchip stockpiles are colonized by Aspergillus fumigatus, a fungus which can infect the human lung. It would be desireable, instead, to use internally generated recycled compost as the bulking agent, while retaining the structural and operational simplicity of the static pile configuration.

To do so, the recycle must consist of i) stable aggregates in the physical sense, to impart porosity, ii) highly stabilized material in the sense of supporting only slight metabolic heat generation, to reserve most of the ventilation system's heat removal capacity for the fresh sludge, iii) dry material, to absorb water from the sludge to improve porosity. Furthermore, the composting process itself should promote drying so that once composting is initiated, porosity progressively improves. These are precisely the tendencies intrinsic to the Rutgers strategy, hence this trial.

MATERIALS AND METHODS SPECIFIC TO SECTION 5

Screened material (woodchips removed) from piles 8 and 9A was used as the bulking agent. Screening was by means of a Royer Model 355 shredder-mixer coupled with a Mogensen sizer (Royer Foundry and Machine Co., Kingston, PA). After the screening the material was stockpiled in the open for approximately 4½ and 3 months, respectively, without deliberate remoistening. At the time of use the pile was cool, the bulk of the material had a moisture content of 39%, and the material had a slight earthy aroma.

Fresh sludge cake and compost were fed by separate conveyer belts into the pug mill for mixing. The feed rates were adjusted by eye to yield one batch with a low recycle ratio (sludge-rich), one batch with an intermediate ratio (roughly equal proportions), and one batch with a high ratio (compost-rich). The ratios actually obtained were determined by calculation based on the moisture content of the sludge (74%), the compost (39%), and the mixture (TABLE 4.).

TABLE 4. PILE CHARACTERISTICS

Pile	Approx pile wet weight (tonnes)	Dry weight recycle ratio (compost/compost + fresh sludge)	Initial moisture content (%)	Initial approx. volume (m^3)
11A	5.4	0.3	69.5	5.3
11B	4.5	0.6	61.5	5.3
11C	3.6	0.8	52.0	5.3

Each compost-sludge mixture was formed into a pile over parallel segments of perforated flexhose within a woodchip bed (Figure 43), fitted with control and monitoring devices (Figures 7 and 44), and covered with woodchips (Figure 45). (It was thought advisable to insulate these small, free-standing, piles with a woodchip cover.) Each pile was ventilated with one 1/3 hp blower operated in the forced pressure mode. Process control was based on temperature feedback, with the thermistor located at position 1 (Figure 43), and the temperature controller was set to 45°C. Timer-scheduled operation was 0.75 min (uninterrupted) per 15 min.

The trial was started on 24 Oct 1980 and terminated on 7 Nov, at which time the woodchip cover was removed (Figure 46). Ambient air temperatures during this period were (°C): mean of the daily highs, 14°; mean of the daily lows, 4°; mean of the daily means, 9°; range of the daily highs and lows, -2° to 21°. Rainfall amounted to 8.0 cm in 3 occurrences.

RESULTS

Pictorial Representation

The periods of temperature feedback control ended on hrs 228, 186, and 102, respectively (see Blower Operation, below). On hr 330 the woodchip cover was removed from all of the piles. A pictorial overview is provided by Figures 44 and 46. Other pairs of photos give "before and after" closeups of each pile (pile 11A, Figures 47 and 48; pile 11B, Figures 49 and 50; pile 11C, Figures 51 and 52). Shrinkage in volume is evident, being greatest in pile 11A, intermediate in pile 11B, and least in pile 11C. This is also the order of sludge (and water) abundance in the mixtures at time-zero.

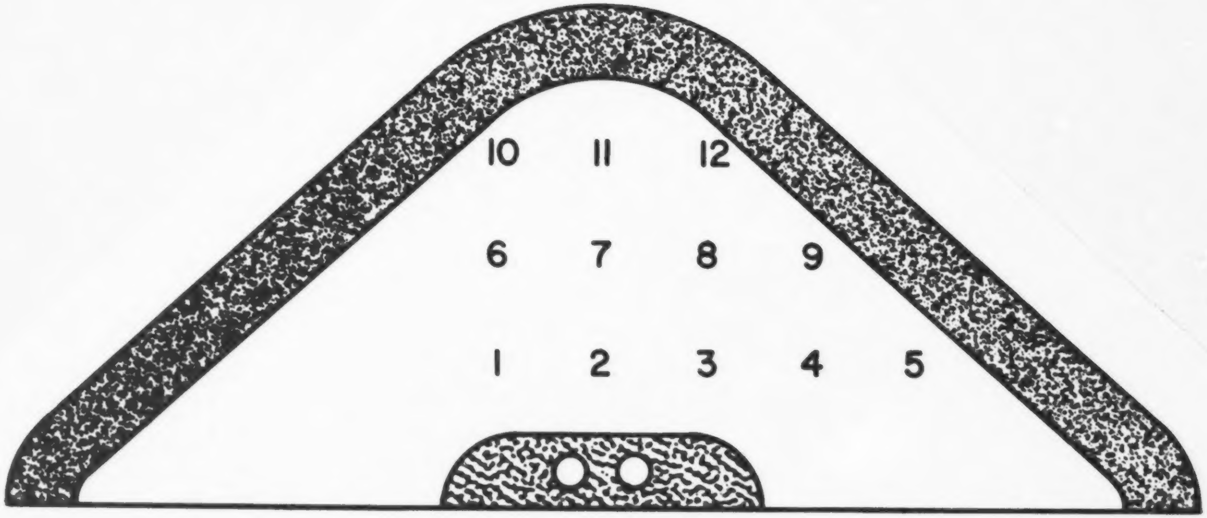

Figure 43. Piles 11A, 11B, and 11C, cross-sectional representation: textured area, woodchip cover and base; clear area, sludge-compost mixture; circles, perforated flexhose. The numbers indicate monitoring and control positions: thermocouples, positions 1 through 12; control thermistor, position 1. The gas sampling probes were positioned as follows: pile 11A, adjacent to positions 2 and 7; pile 11B, adjacent to position 2; pile 11C, adjacent to position 7. The blower was operated in the forced-pressure mode.

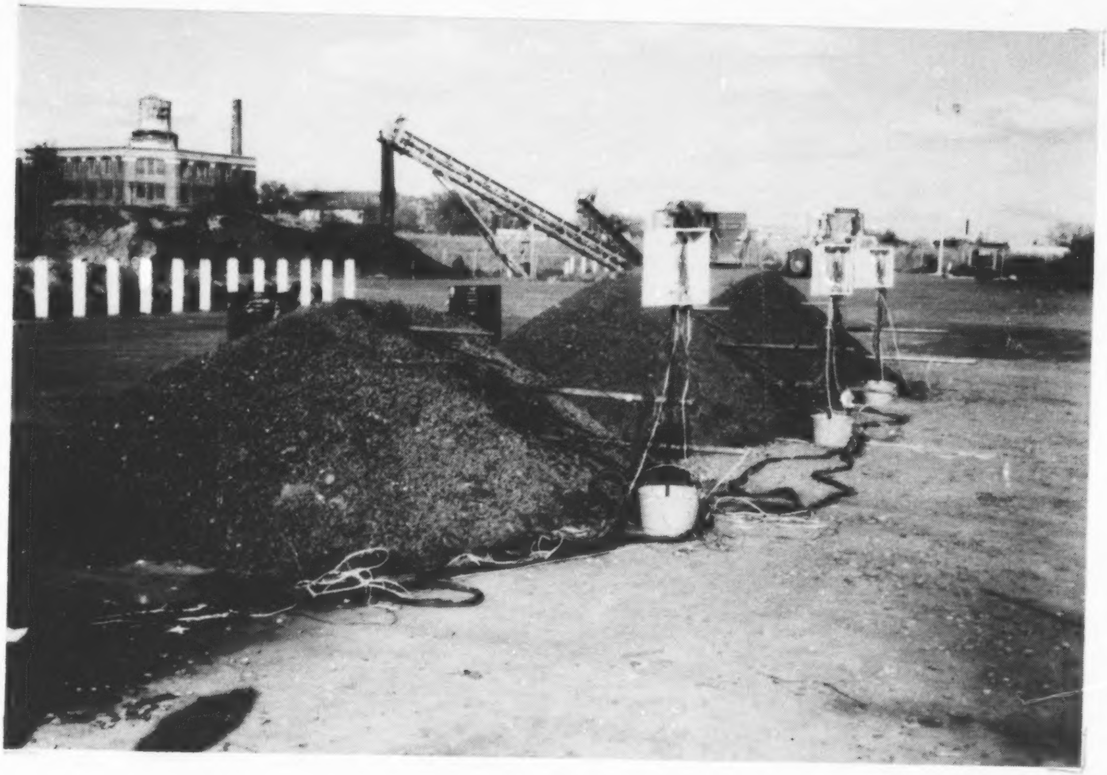

Figure 44. Piles 11A, 11B, and 11C, before composting. The dowels extend from the pile, and the thermocouple leads are organized at subjunction boxes. The thermistor was at the end of the lowest dowel. Modified oil drums served to cover the blowers at the rear of the piles. Photo by F.C. Miller.

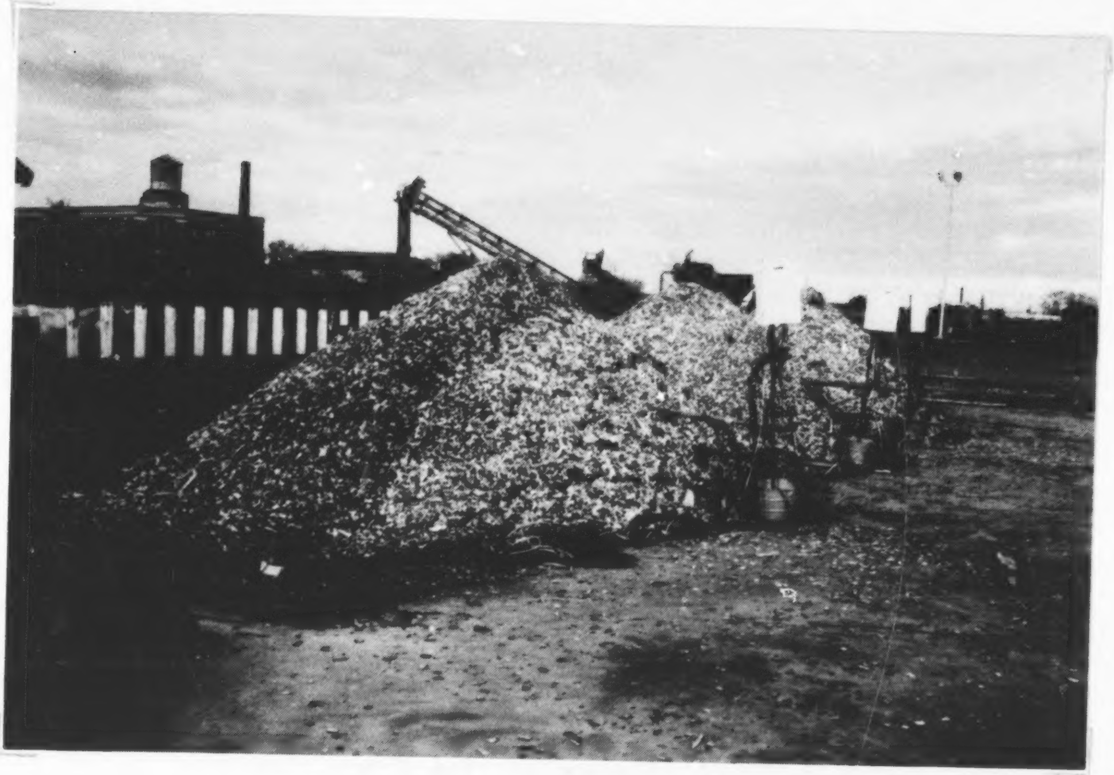

Figure 45. Same as Fig. 44, after covering with woodchips. Photo by F.C. Miller.

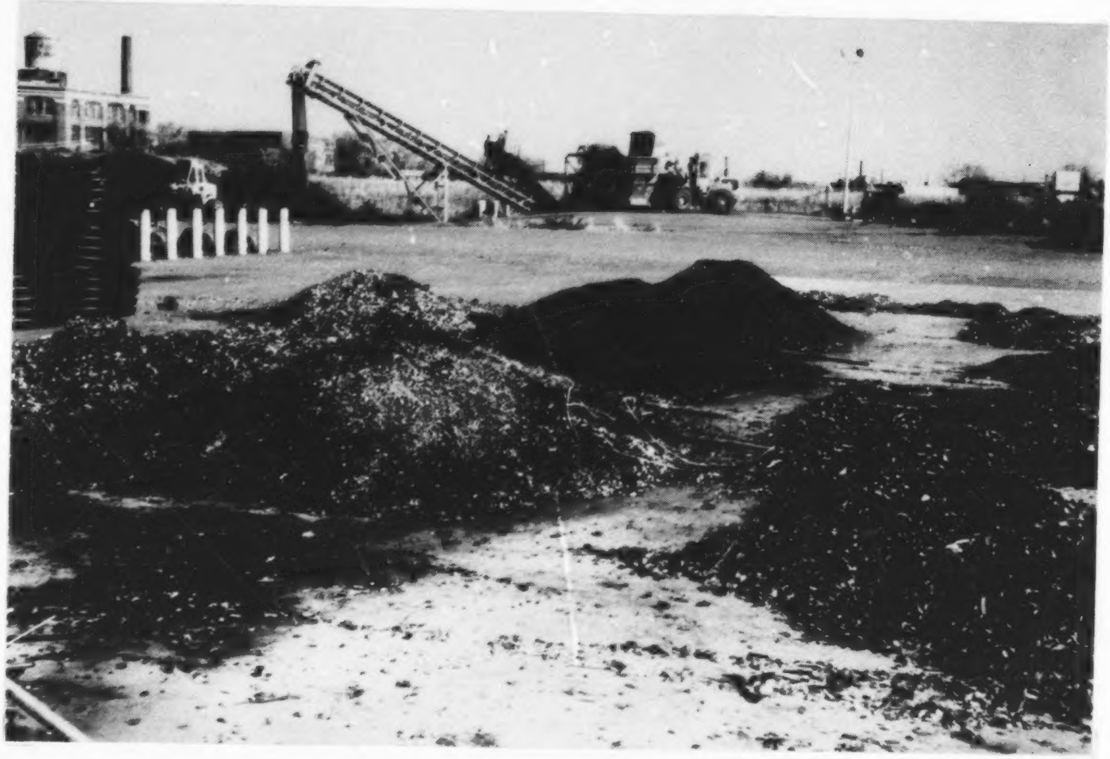

Figure 46. Overview of piles after composting. The woodchip cover had been removed. Photo by F.C. Miller.

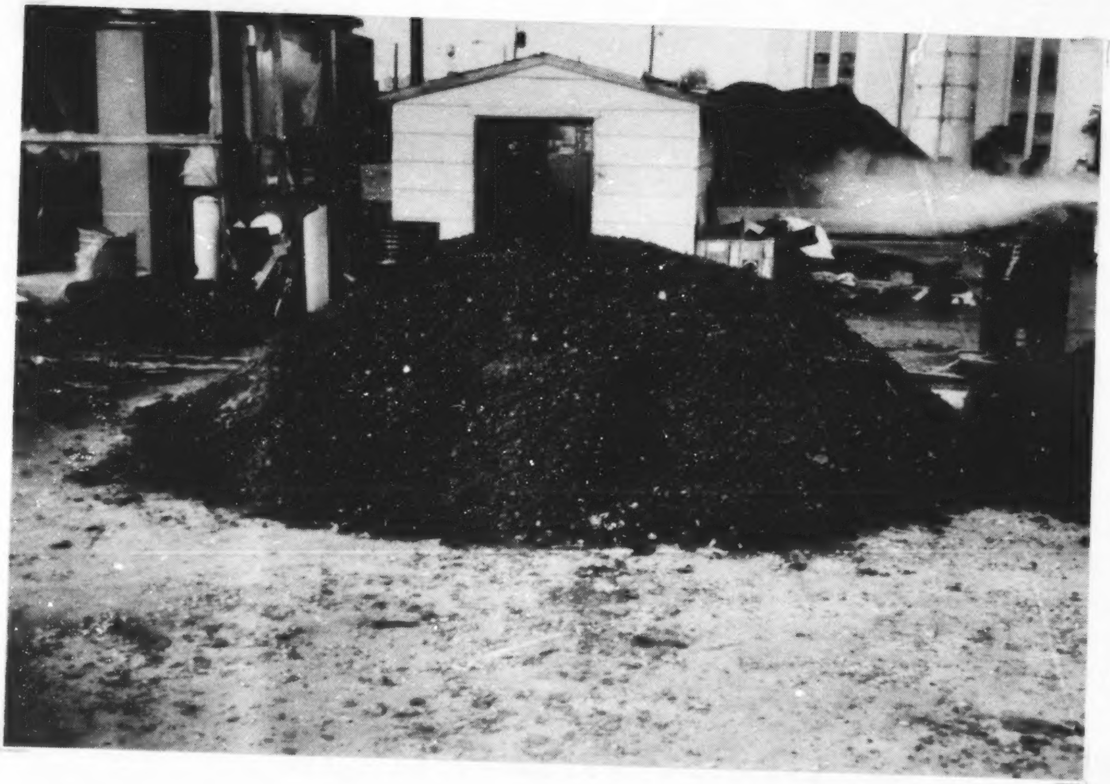

Figure 47. Pile 11A, before composting. Photo by F.C. Miller.

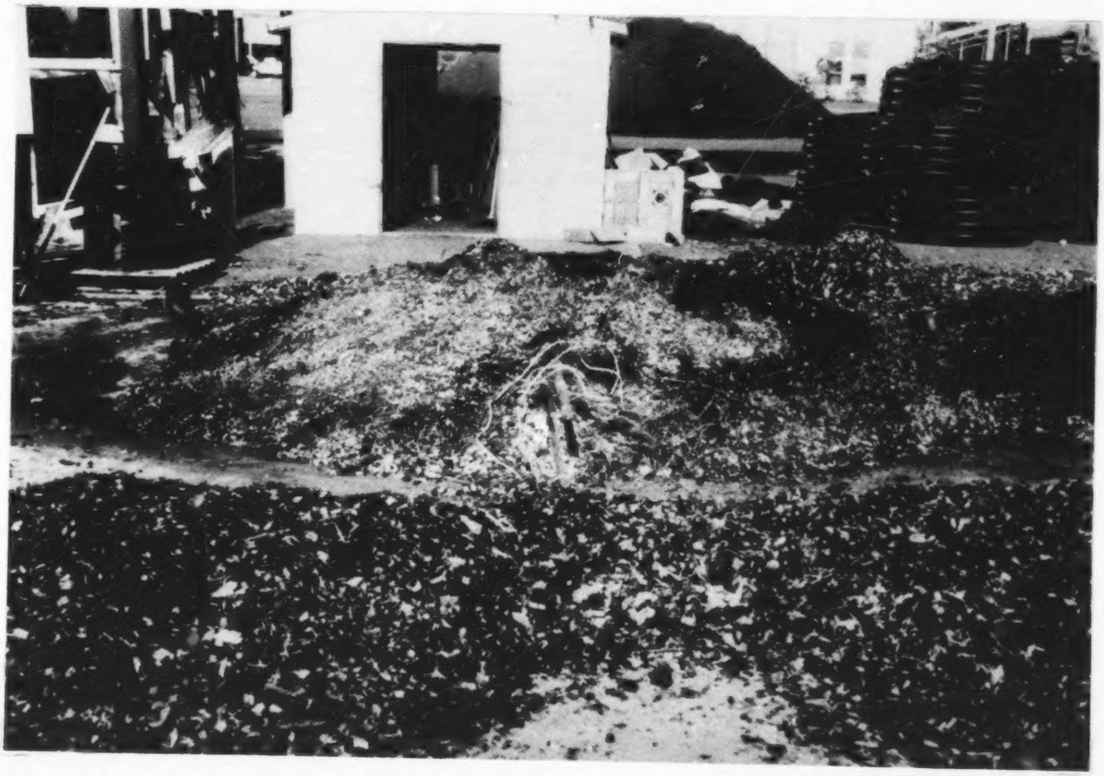

Figure 48. Pile 11A, after composting. The woodchip cover has been removed. Photo by F.C. Miller.

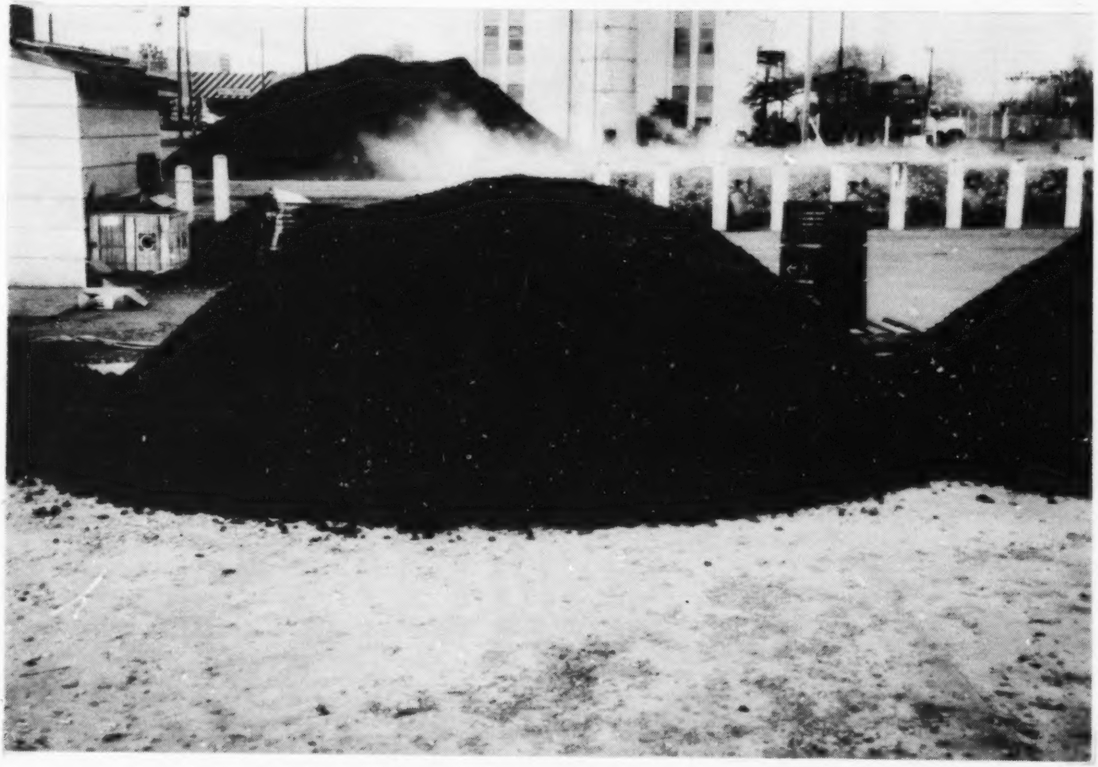

Figure 49. Pile 11B, before composting. Photo by F.C. Miller.

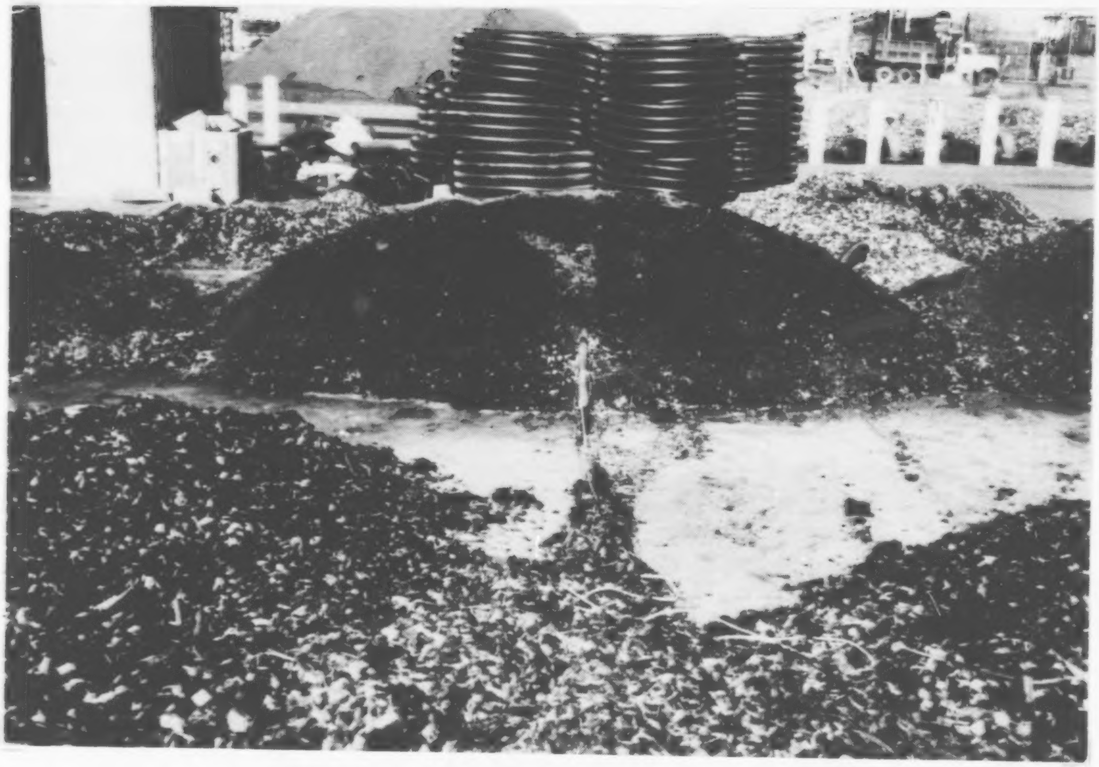

Figure 50. Pile 11B, after composting. The woodchip cover has been removed. Photo by F.C. Miller.

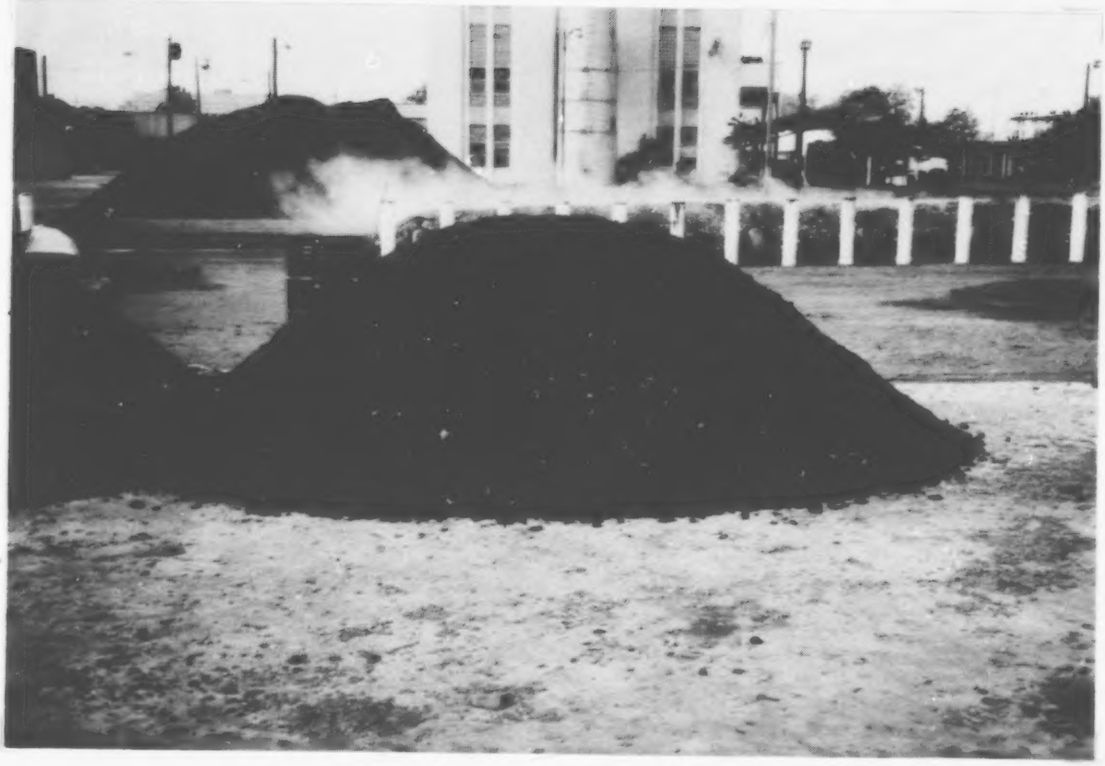

Figure 51. Pile 11C, before composting. Photo by F.C. Miller.

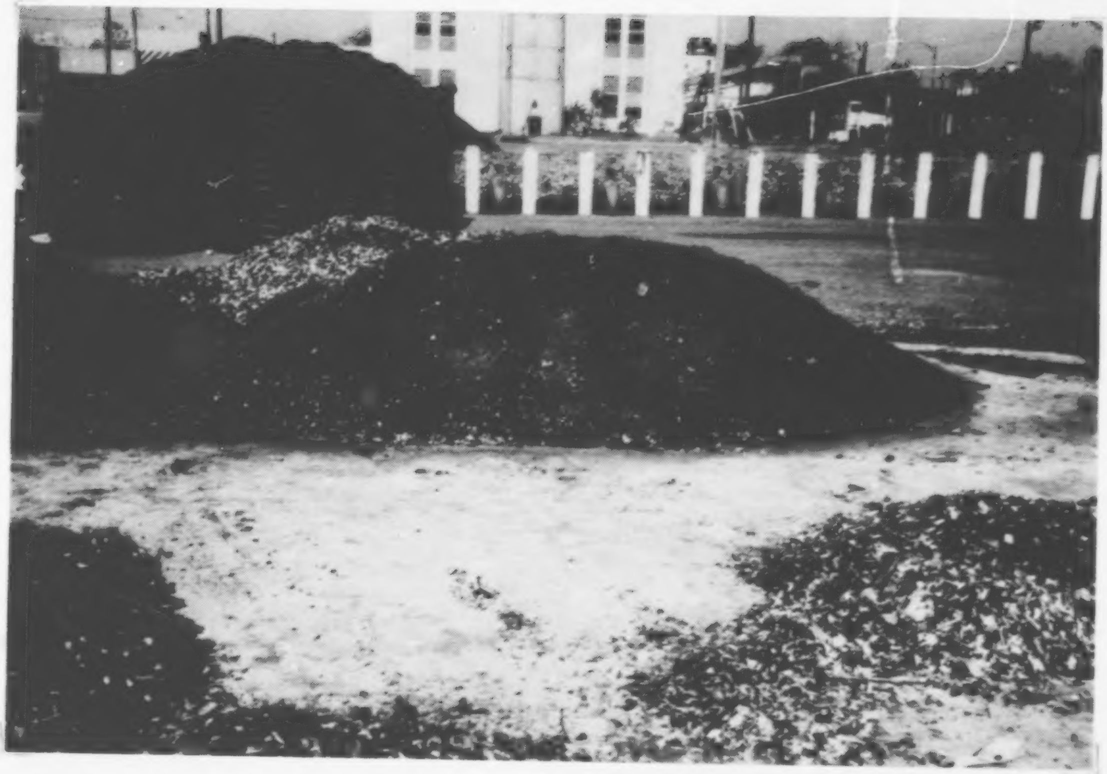

Figure 52. Pile 11C, after composting. The woodchip cover has been removed. Photo by F.C. Miller.

Blower Operation

The duration of temperature feedback control (Figures 53, 54 and 55) was longest in pile 11A (hr 22 to 228), intermediate in pile 11B (hr 16 to 186) and briefest in pile 11C (hr 14 to 102). In piles 11A and 11B the peak demand for ventilation utilized approximately 55% of the blower capacity. The comparable value for pile 11C was 25%. The comparative overall demand for ventilation was assessed in terms of the total blower operation time during the period of feedback control (baseline included). Setting the greatest demand equal to 100, the values were: pile 11A, 100; pile 11B, 92; pile 11C, 23.

Pile Temperature

The temperature plots for the thermistor and overlying positions are given in Figures 56, 57, and 58. At the thermistor position the set point temperature (45°C) was precisely maintained during the period of feedback control. With some exceptions, notably at probe 11B6, the higher positions experienced higher temperatures in the usual pattern of a systematic gradient. The gradient was most clearly established in pile 11C (compost-rich). In other parts of the pile the temperature control was less precise (see Appendix C). The temperature observations at all of the positions during the feedback period, and other data, are summarized in TABLE 5.

Pile Atmosphere

The lowest O_2 levels recorded during the period of feedback control were as follows: 11A (high probe position), 14.5%; 11B (low probe position), 16.8%; 11C (high probe position), 13.3%. The corresponding peak CO_2 levels were 2.8%, 1.8% and 6.8% (Figures 59, 60, 61 and 62).

Moisture Content

The initial moisture contents (11A, 70%; 11b, 61%; 11C, 52%) reflected the differences in the sludge-compost mix ratios (Figure 63). Water losses were positively correlated with the amount of sludge in the mix. The minimum moisture contents, observed prior to the terminal observation, were: pile 11A, 29%; pile 11B, 21%; pile 11C, 23%. The terminal values were slightly higher.

Visual, Tactile, and Aesthetic Qualities

At termination, the piles were bisected and examined. The material comprising the outer rim of the sludge-rich pile 11A (the "toes") was wet and pasty, with an unpleasant odor. This material had not composted appreciably. The bulk of the pile however, had composted extensively, was dry, and had a greyish cast seemingly imparted by mycelial growths. This part the pile consisted of chunks of material, ranging in size from that of golfballs to boulders. The individual units were resistant to breakage by hand. Unlike the outer rim, the bulk of the material had no conspicuous odor.

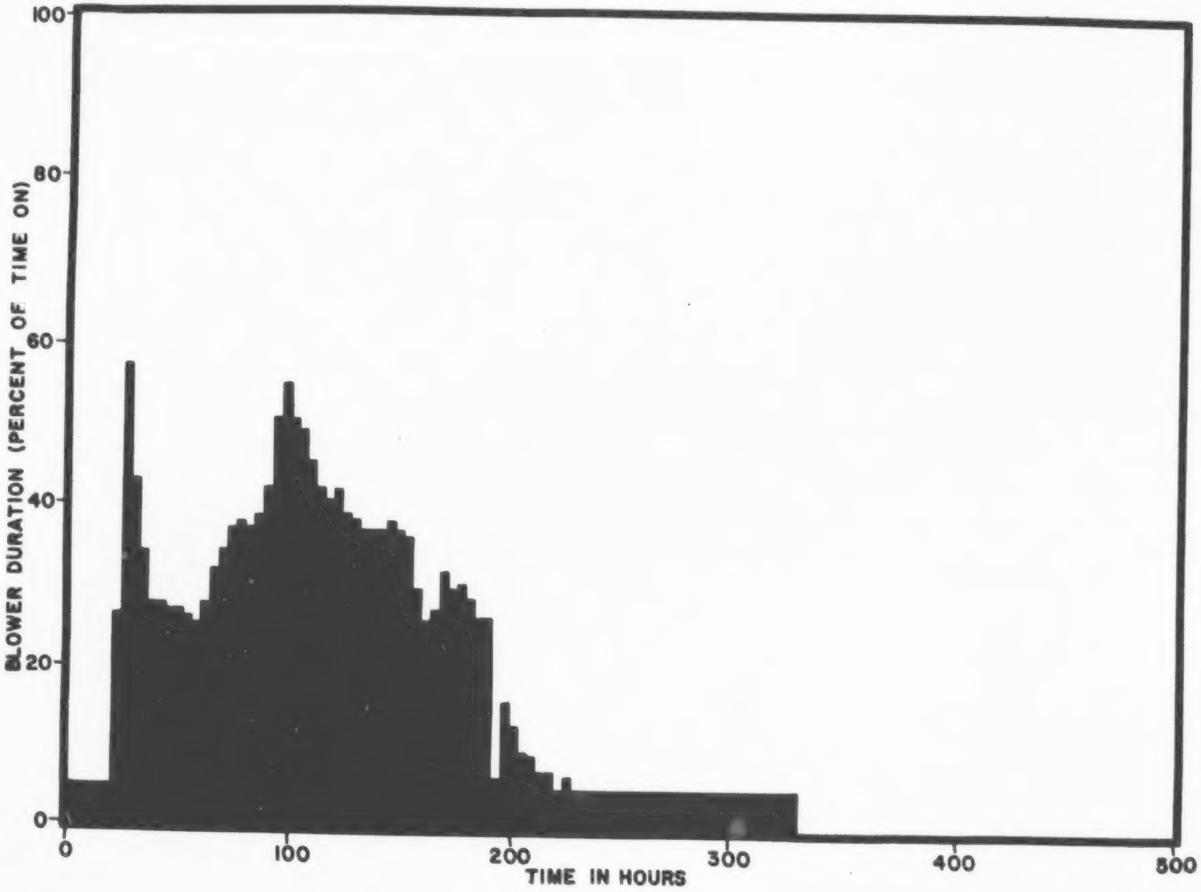

Figure 53. Pile 11A, blower operation. The baseline represents operation as scheduled by timer, and the area above the baseline represents operation through the temperature-feedback control system. The blower was operated in the forced-pressure mode.

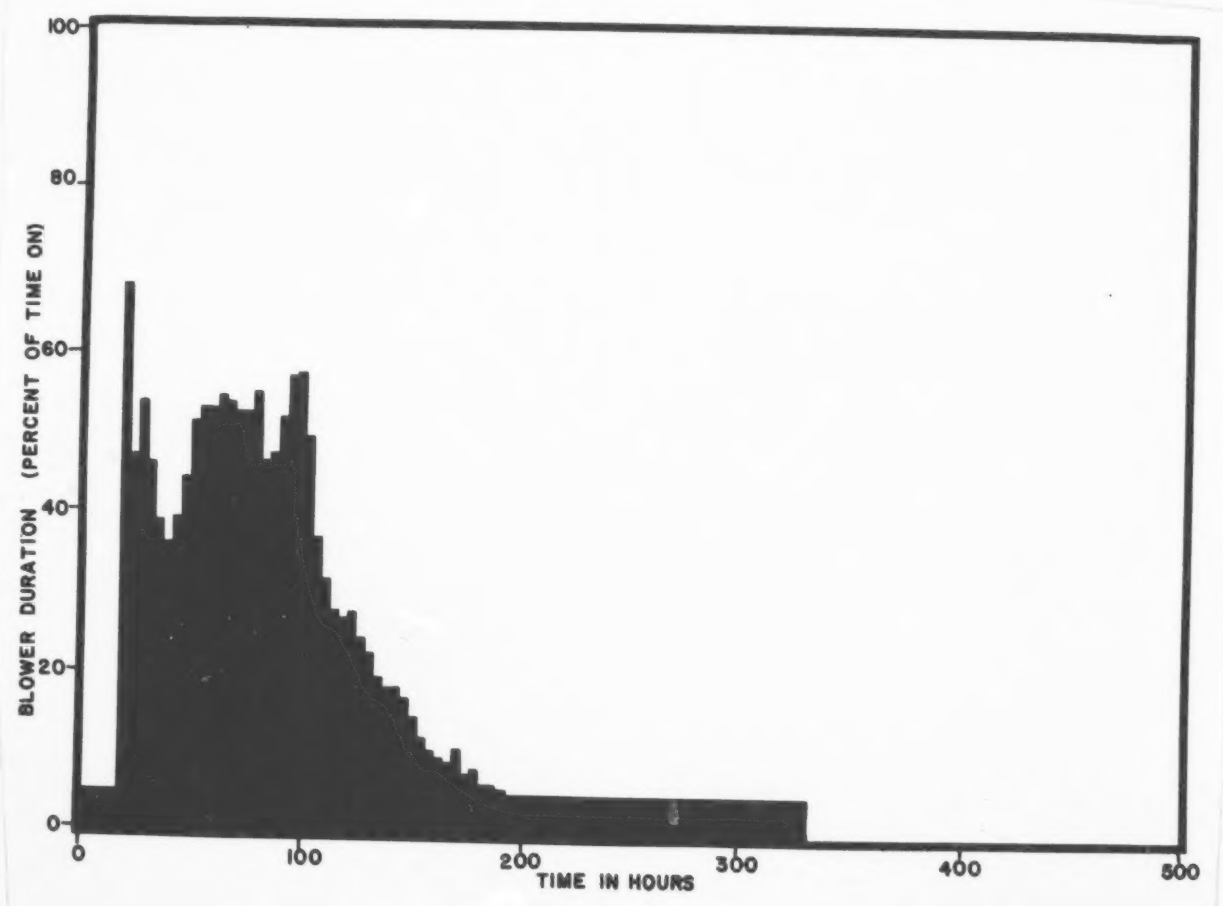

Figure 54. Pile 11B, blower operation. The baseline represents operation as scheduled by timer, and the area above the baseline represents operation through the temperature feedback control system. The blower was operated in the forced-pressure mode.

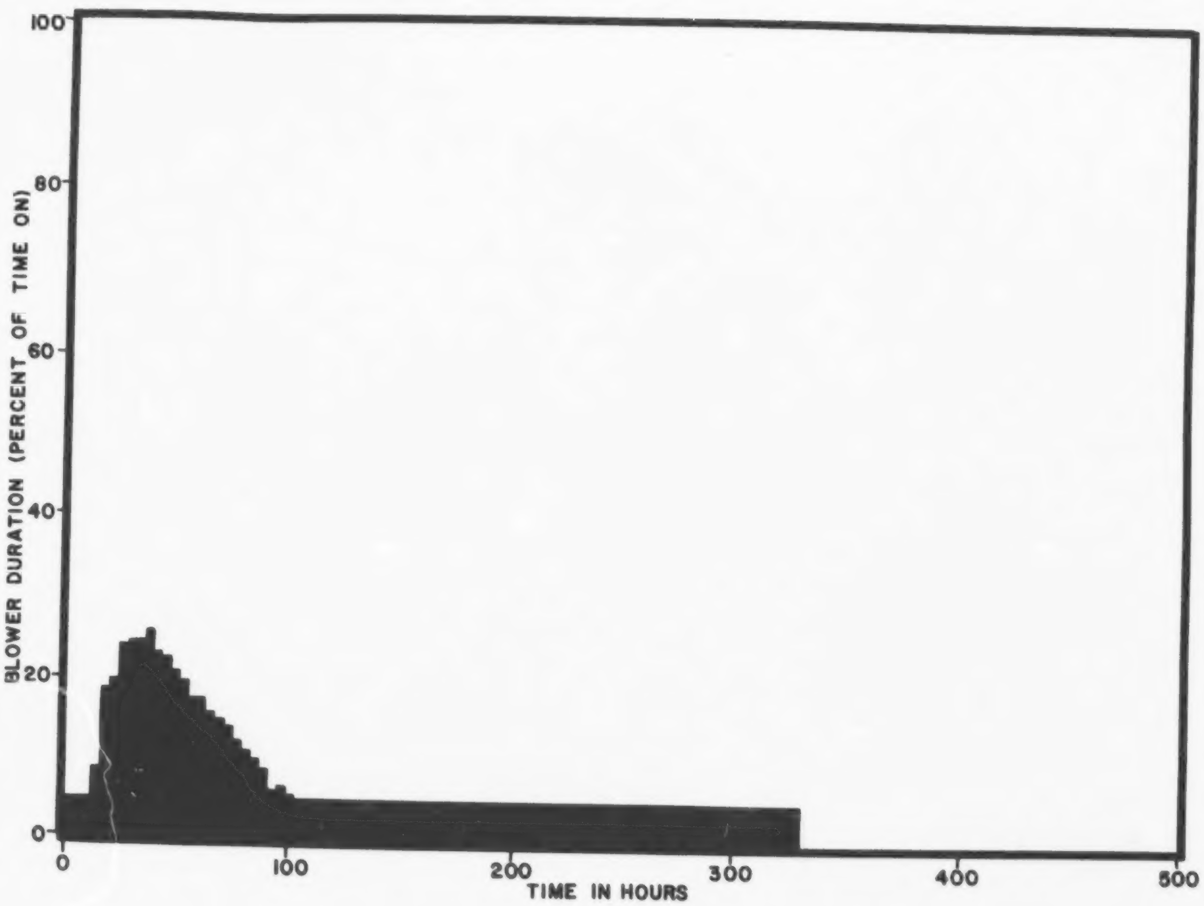

Figure 55. Pile 11C, blower operation. The baseline represents operation as scheduled by timer, and the area above the baseline represents operation through the temperature feedback control system. The blower was operated in the forced-pressure mode.

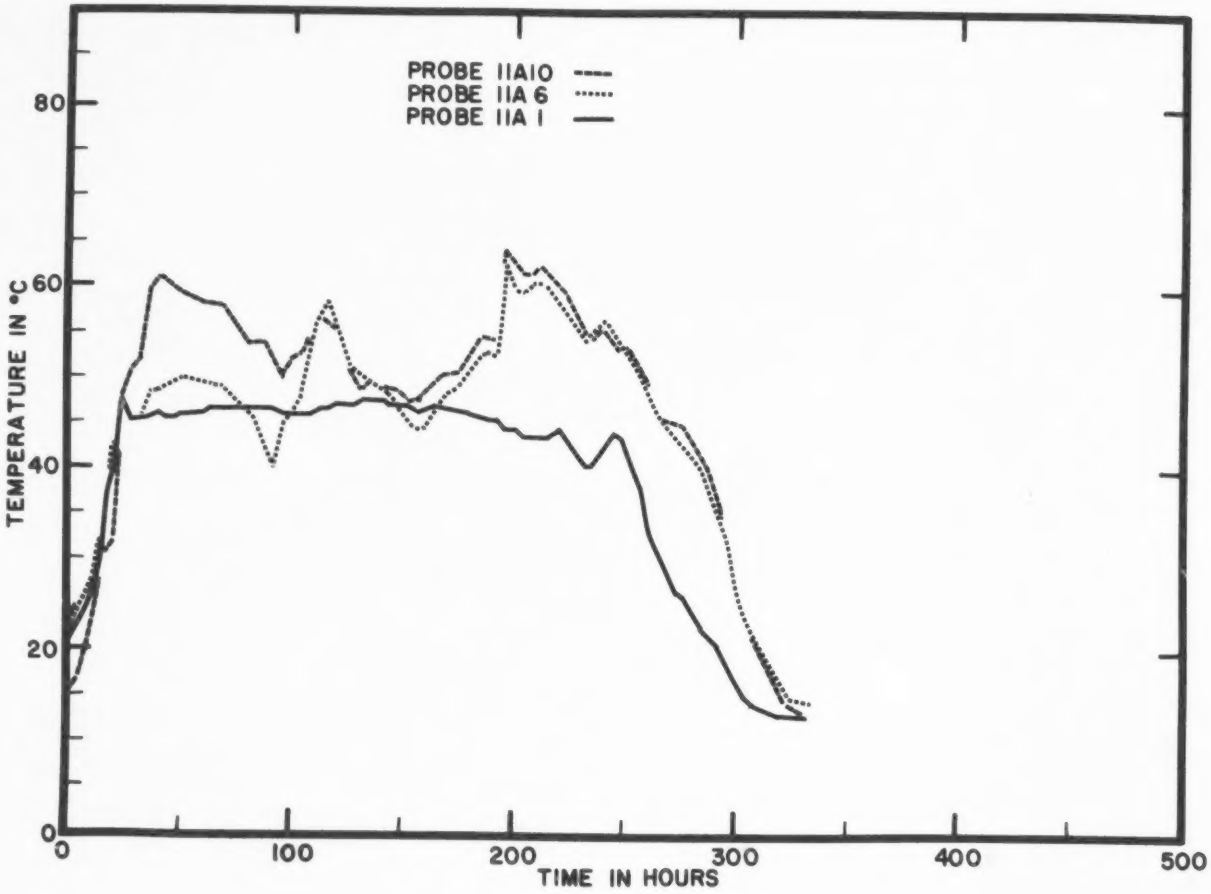

Figure 56. Pile 11A, temperature at the innermost vertical series of thermocouples.

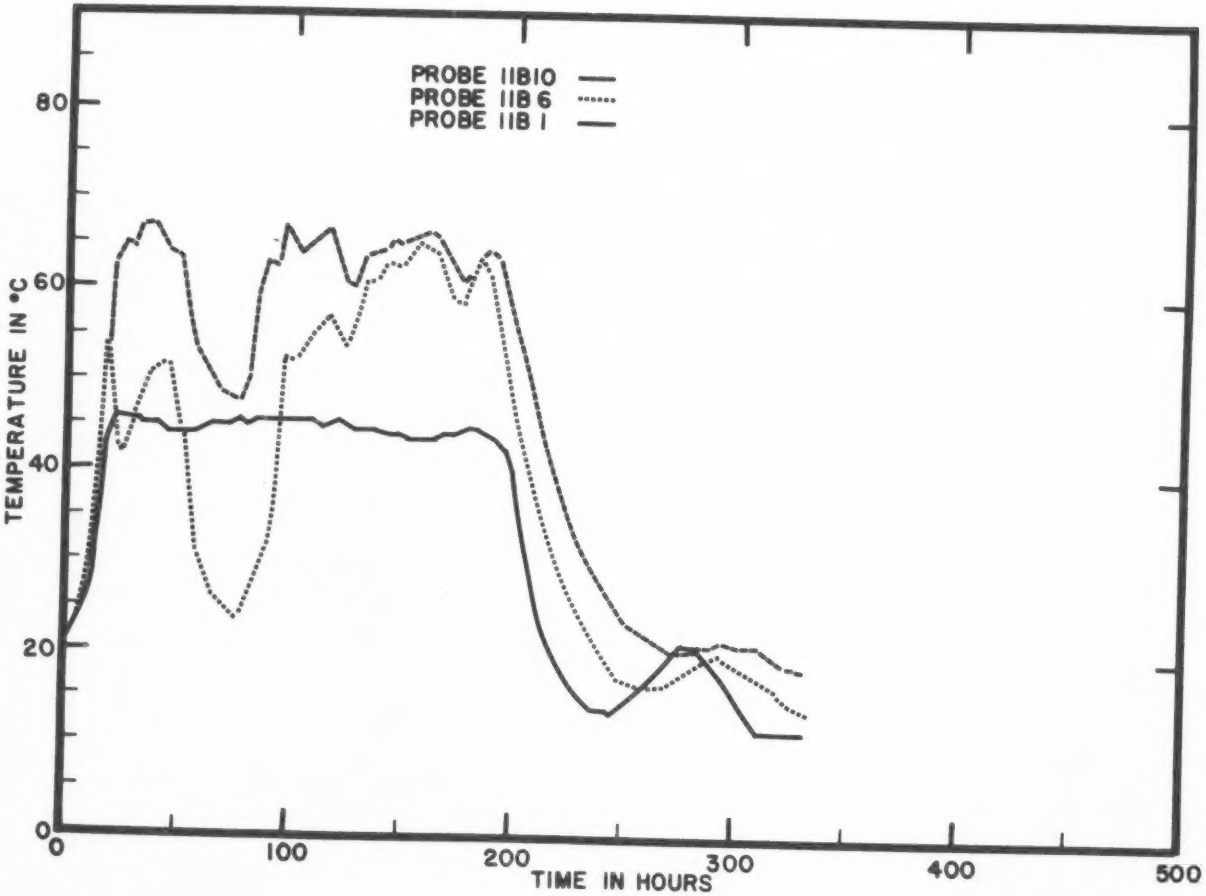

Figure 57. Pile 11B, temperature at the innermost vertical series of thermocouples.

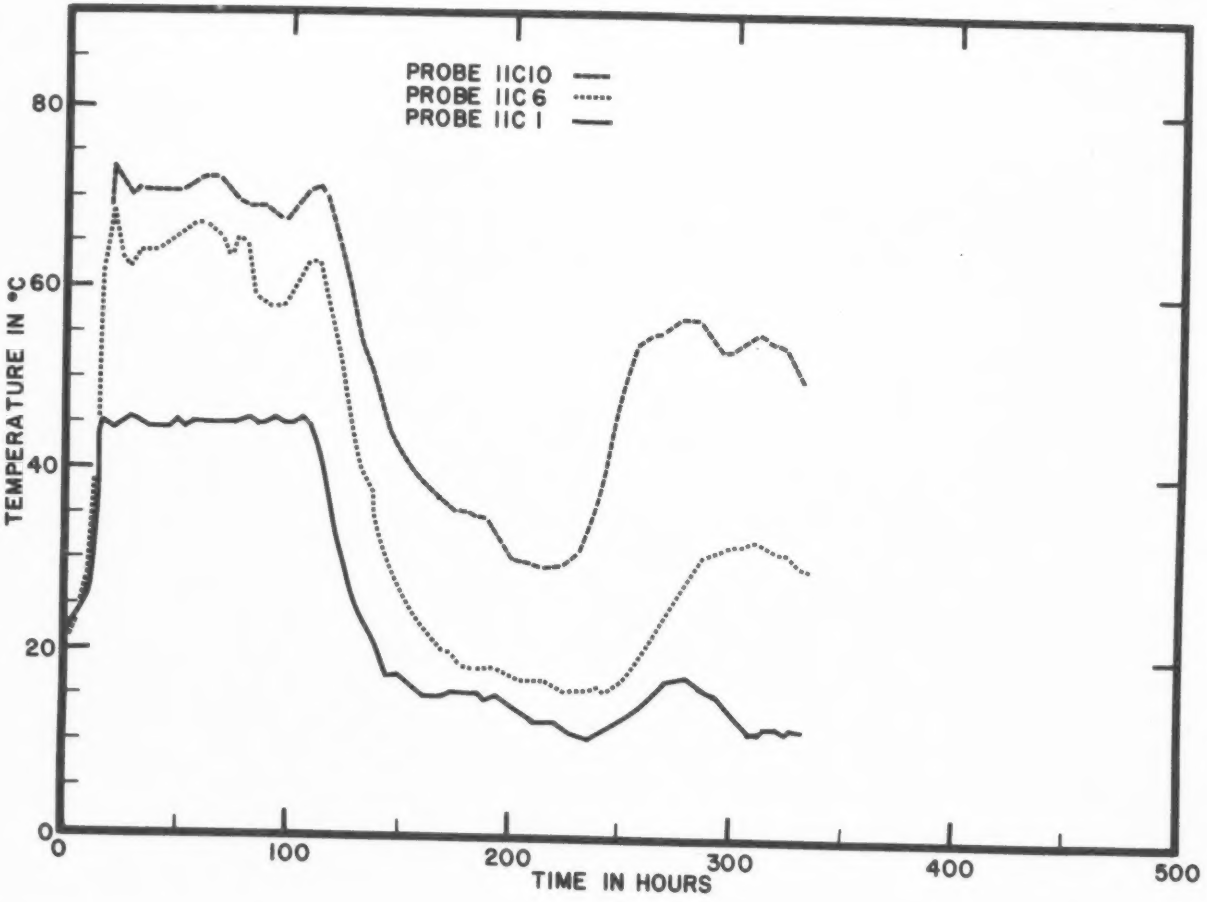

Figure 58. Pile 11C, temperature at the innermost vertical series of thermocouples.

TABLE 5. DATA SUMMARY FOR SECTION 5[*]

	Pile		
	11A	11B	11C
Recycle ratio	0.3	0.6	0.8
Temperature (during period of feedback control)			
Period (hr)	22-228	16-186	14-102
Range (°C)	29-73	9-71	11-75
Median (°C)	53	46	59
Observations (no.)	624	516	264
% observations ≥ 60°C	24	20	46
Interstitial gases (time 0 to hr 332)			
O_2 Range (%)	12.8-21	16.8-21	13.3-21
O_2 Median (%)	20.8	20.3	20.8
Observations (no.)	168	84	84
CO_2 Range (%)	<0.1-8.6	<0.1-1.8	<0.1-6.8
CO_2 Median (%)	<0.1	0.2	<0.1
Observations (no.)	168	84	84
Moisture content (%)			
Time-zero	70	61	52
150 hr	32	28	24

[*] Rutgers process control strategy applied to all of the piles. Dry weight recycle ratio = recycle/recycle + fresh sludge.

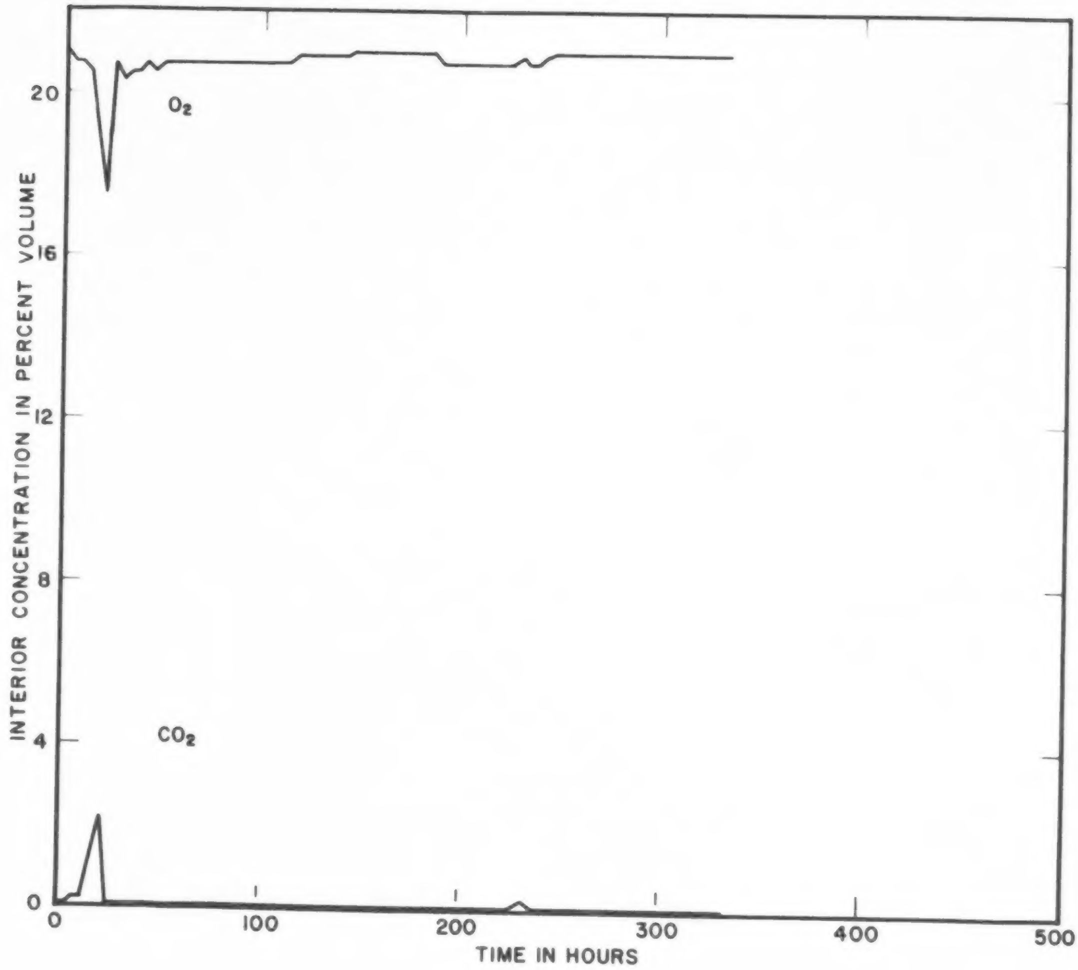

Figure 59. Pile 11A, concentrations of O_2 (upper curve) and CO_2 (lower curve). The gas sampling probe was adjacent to position 2.

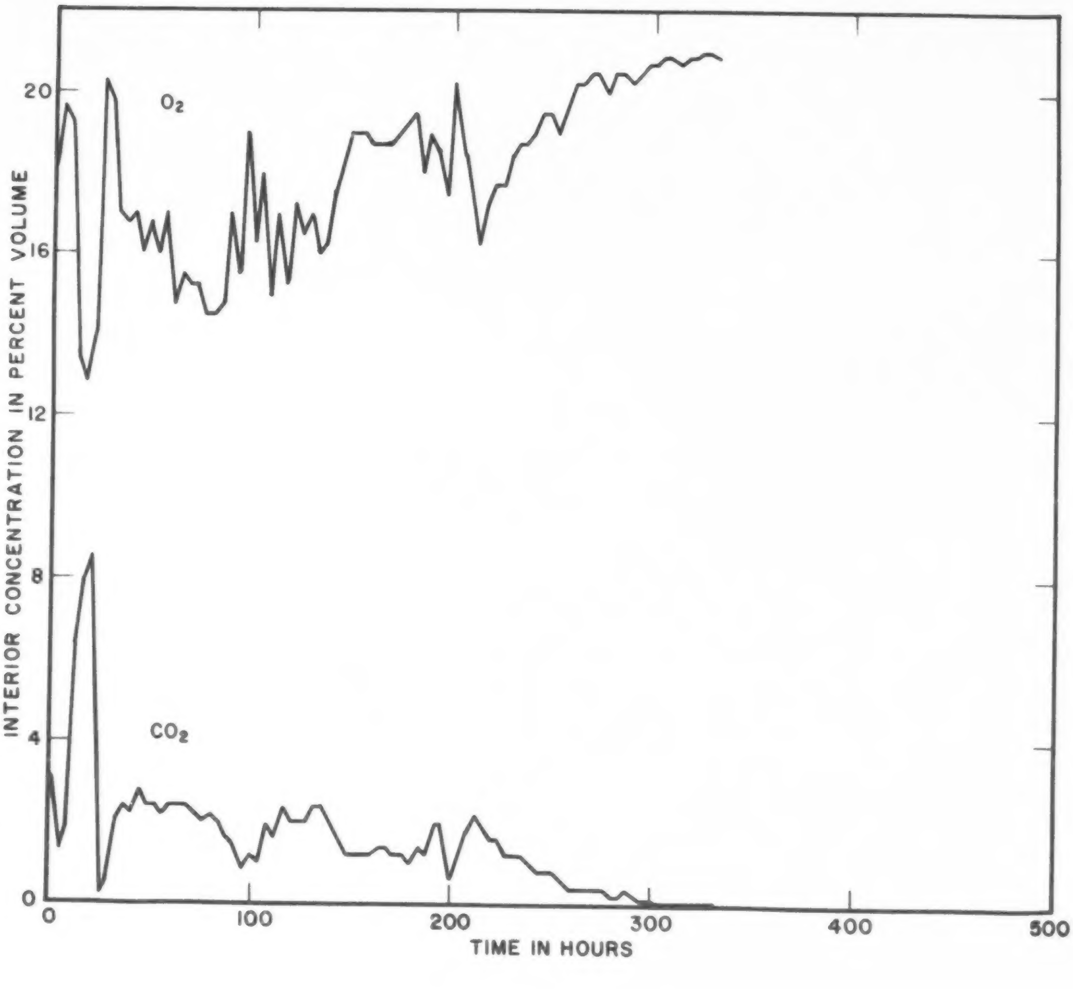

Figure 60. Pile 11A, concentrations of O_2 (upper curve) and CO_2 (lower curve). The gas sampling probe was adjacent to position 7.

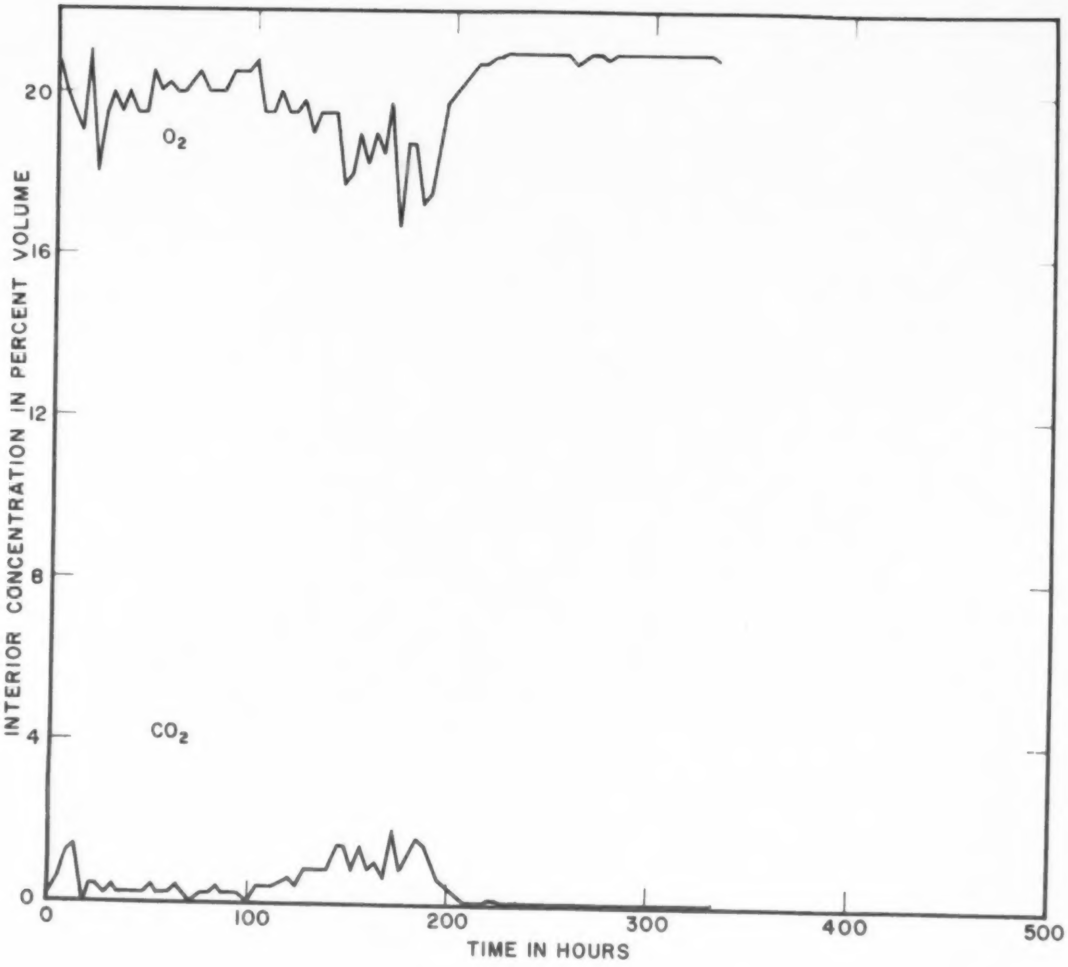

Figure 61. Pile 11B, concentrations of O_2 (upper curve) and CO_2 (lower curve). The gas sampling probe was adjacent to position 2.

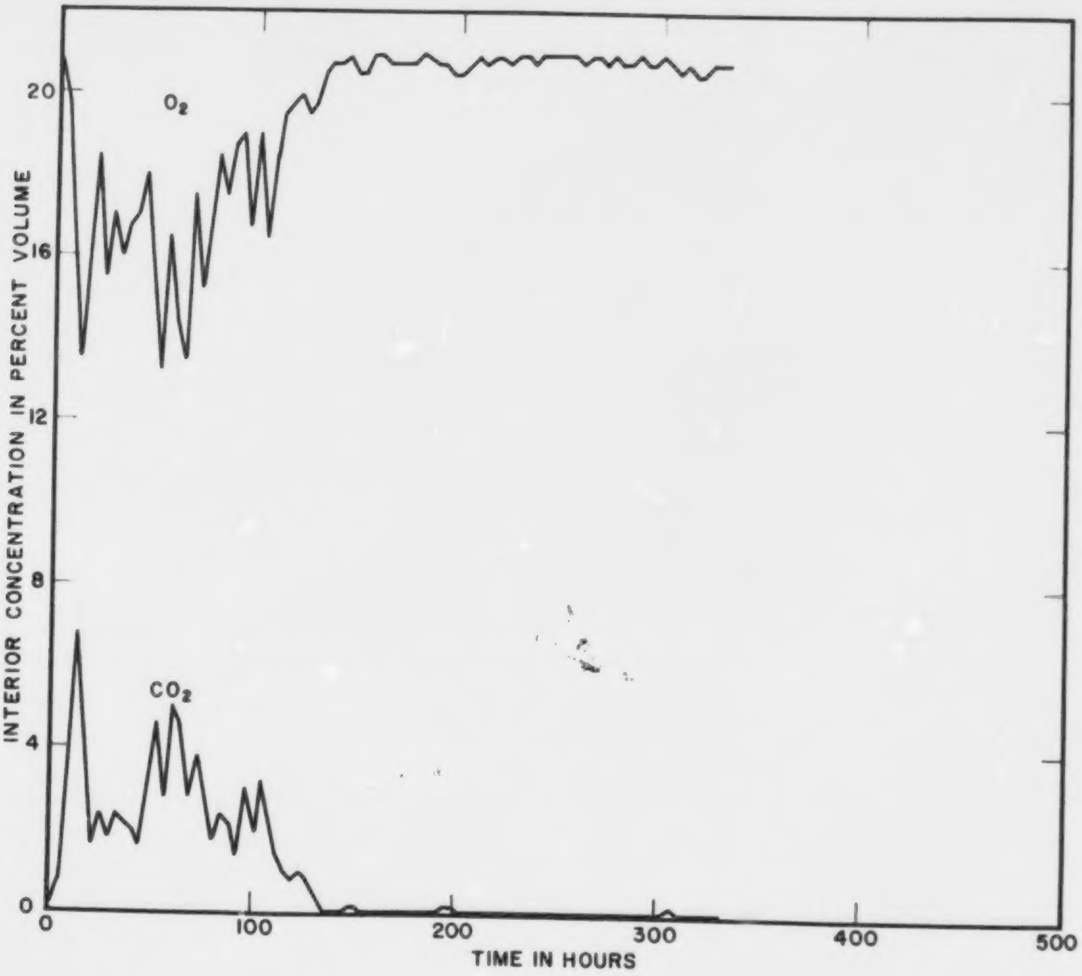

Figure 62. Pile 11C, concentrations of 0_2 (upper curve) and $C0_2$ (lower curve). The gas sampling probe was adjacent to position 7.

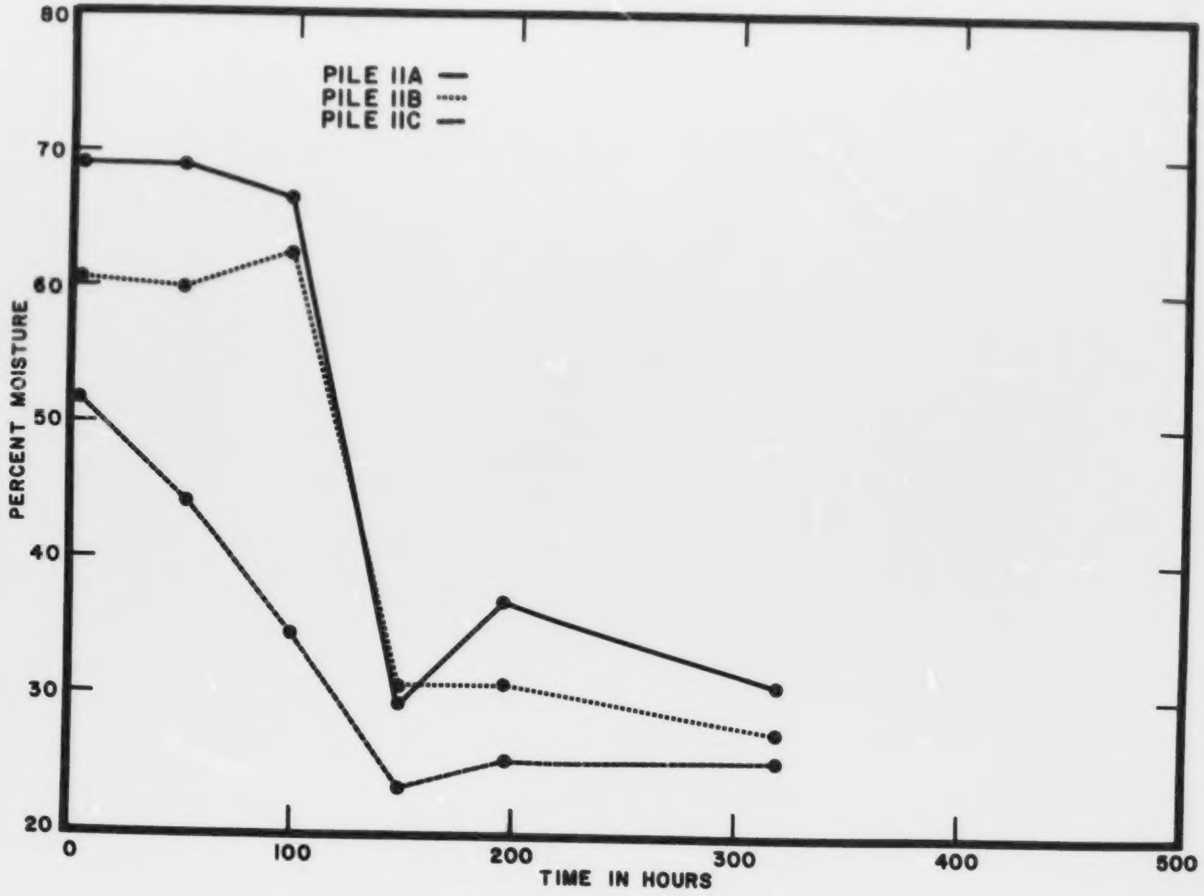

Figure 63. Piles 11A, 11B, and 11C, moisture content. Samples taken from central interior locations.

At termination the material in piles 11B (intermediate) and 11C (compost-rich) was uniformly dry, granular, and brown. The material in both of these piles had a slight earthy aroma.

DISCUSSION

A noticeable difference in behavior attributable to the replacement of woodchips with compost is that, lacking the rigidity of the woodchip matrix, these piles shrunk considerably in volume. Other differences that might also be attributable to the use of compost as the bulking agent are: a relatively brief period of temperature feedback control (faster processing); less precise control of temperature; faster drying.

The major significance of this trial is that the possibility of using recycled compost as the bulking agent in static pile configuration was demonstrated. Others have demonstrated use of recycled compost in this capacity in conjunction with "windrow composting," in which the mass is mechanically agitated (42). Agitation is energy intensive, however, and affords little control over temperature and oxygen.

It was anticipated that pile 11A would fail, since it was so rich in sludge (recycle ratio, 0.3). Yet, the bulk of the pile composted satisfactorily, judging from all of the parameters. The outer material was isolated from the airstream, and did not compost. For routine use higher recycle ratios, as represented by piles 11B and 11C, are indicated. Nevertheless, the performance of pile 11A indicates a degree of processing resilience in conjunction with the use of recycled compost.

Owing to compactability leading to greater resistance to airflow, sludge-compost mixtures may be more subject to a height restriction than sludge-woodchip mixtures. This also indicates use of higher recycle ratios. Further field experimentation is needed to define the height limitation.

SECTION 6

COMPARISON BETWEEN THE RUTGERS STRATEGY AND BELTSVILLE PROCESS: MATERIALS BALANCE

INTRODUCTION

The outcome of processing in terms of materials balance impacts on facility design with respect to composting area, storage area, and machinery needs for materials handling and transport. Moreover the amount and nature of the process residue, relative to the sludge, strongly influences the possibilities for ultimate disposal/resource recovery. As such, materials balance is a major determinant of construction and operating costs, disposal options, and indeed of the utility of composting as a waste treatment technology.

In Section 3, the Rutgers and Beltsville approaches were compared in terms of blower operation, temperature, O and CO_2 levels, and moisture content. This comparison is extended herein, based on certain of these data and related analyses. Also, materials balance is estimated for the piles described in Section 5. These employed recycled compost as the bulking agent, and were managed according to the Rutgers strategy.

PROCEDURE FOR CALCULATING AIRFLOW AND MATERIALS BALANCE

An airflow delivery of 807 m^3/hr (28,500 ft^3/hr) per blower was assumed, based on the manufacturer's specifications at 5.1 cm (2 in.) of water head.

The mass of the mixture after composting was calculated based on the equation:

$$k = \frac{M_i MC_i - M_f MC_f}{M_i(1-MC_i) - M_f(1-MC_f)}$$

where:

M_i = initial mass
MC_i = initial moisture content
MC_f = final moisture content
k = 8.07 (Rutgers strategy), or 8.33 (Beltsville Process).

The constant k is the ratio mass water vaporized/mass solids decomposed, as derived in Appendix A-6. With air exiting from the composting mass at 60°C and 100% relative humidity (representative of the Rutgers strategy), the constant is 8.07; at 70°C and 100% RH (representative of the Beltsville Process), it is 8.33. Mixture refers to sludge and woodchips, or sludge and recycled process residue ("compost").

Rearranging:

$$M_f = \frac{M_i[k(1-MC_i) - MC_i]}{k(1-MC_f) - MC_f} \qquad \text{(ii)}$$

Since the values for M_i and MC_i are known, the initial weights of dry matter and water can be calculated. Having derived M_f, and knowing MC_f, the final weights of dry matter and water can be calculated. At this stage the estimates refer to the mixture of sludge and woodchips, or sludge and recycled compost.

With respect to the sludge-woodchip mixture the estimate was converted to total sludge solids decomposition, and to sludge volatile solids decomposition, based on a sludge-woodchip ratio of 1 tonne sludge cake per 1.7m^3 woodchips (1 ton per 2 yd^3), and the following nominal characteristics: sludge cake moisture content, 75.5%; sludge cake volatile solids content, 73.5%; woodchip bulk density, 234 kg/m^3 (394 lb/yd^3) (43). Also, it was assumed for the purpose of calculation that the woodchips did not decompose. To estimate the volatile solids decomposition of the mixture of sludge and recycled compost, the compost was assigned a volatile solids content of 54.5% based on values given in TABLE 6.

AIRFLOW AND MATERIALS BALANCE ESTIMATES

The airflow and materials balance estimates for the piles using woodchips as the bulking agent are given in TABLE 6. For piles 7, 8, and 9A, the mean total air delivery during 12.4 days of composting was 9,950m^3/tonne (319,000 ft^3/ton). For pile 9B this was 20.8 days and 2330 m^3/tonne (74,500 ft^3/ton). Thus, mean air delivery to the Rutgers piles was 4.3x greater. The comparable values for mean and peak delivery were 8x greater and 15x greater, respectively. The need for more air reflects the more extensive waste decomposition.

As is characteristic of feedback control (Rutgers), mean and peak usage differed, being 37.0 and 95.1m^3/tonne-hr, respectively (1,190 and 3,050 ft^3/ton-hr). With timer control (Beltsville) mean and peak differed slightly, only because the blower schedule was adjusted manually. This was as prescribed (9), in response to high levels of O_2.

With application of the Rutgers strategy, a mean of 16.0% of the sludge-woodchip mixture was decomposed in 12.4 days. The comparable estimate for the Beltsville Process is 4.3%, in 20.8 days. Assuming for calculation purposes that the woodchips were not decomposed microbially (a reasonable approximation at these temperatures and times), total sludge solids decomposition amounted to 41.8% (mean value) and 11.3%, respectively. In terms of sludge volatile solids the estimates are 56.9% and 15.4%. Regardless of the fraction (sludge-woodchips mixture, or total sludge solids, or sludge volatile solids), the Rutgers strategy induced an estimated 3.7x more decomposition in approximately half the time. With respect to water the removals amounted to 78.2% and 19.4%, indicating 4x more removal in approximately half the time.

TABLE 6. EFFECT OF CONTROL STRATEGY ON AIR USAGE AND MATERIALS BALANCE[*]

	Process control strategy[†]			
	Rutgers			Beltsville
	Pile 7	Pile 8	Pile 9A	Pile 9B
Period (hr)	0-344	0-170	0-380	0-500
Air delivery (m^3/initial wet tonne)				
Total	13,100	7,180	9,580	2,330
Mean (hr^{-1})	38.1	42.1	30.9	4.7
Peak (hr^{-1})	81.2	71.2	133	5.6
Air delivery (ft^3/initial wet ton x 10^3)				
Total	421	230	307	74.5
Mean (hr^{-1})	1.22	1.35	0.990	0.149
Peak (hr^{-1})	2.60	2.28	4.28	0.192
Material decomposed (% of initial dry weight)				
Overall sludge-woodchip mixture	15.9	11.8	20.4	4.3
Sludge total solids[‡]	41.6	30.8	53.1	11.3
Sludge volatile solids[‡]	56.6	41.8	72.3	15.4
Water removed (% of initial)	78.9	74.8	80.9	19.4

[*] Certain entries given in both metric and English units.

[†] For piles 7 and 8 the calculation is based on the period from time-zero to the cessation of temperature feedback control (= resumption of timer-scheduled blower operation). For pile 9A it was based on the period from time-zero to hr 380 (scheduled operation not resumed because the timer was disconnected during feedback control). For pile 9B it was based on the period from time-zero to hr 500. Where necessary, the corresponding value for MC_f was derived through interpolation.

[‡] The calculation was made as if decomposition of woodchips were nil.

The materials balance estimates for the piles using recycled compost bulking agent are given in TABLE 7. Performance was comparable to that obtained with woodchip bulking agent in conjunction with the Rutgers strategy (compare to TABLE 7, piles 7, 8, and 9A). Except that air delivery to pile 11B was somewhat high, the pattern of results is consistent with the strength of the mixtures. Thus pile 11A, which had more fresh sludge than pile 11C, exerted a greater demand for ventilation and lost more solids and water. Being richer in sludge, its potential for heat generation, blower demand, and vaporization was greater.

DISCUSSION

Composting is a robust process such that it is possible (though not desireable) to design and operate a facility without benefit of a coherent process control strategy. The process' robustness stems from two factors. First, microbial self-heating (the underlying phenomenon) commences spontaneously, even if conditions of nutrition, moisture content, and gas exchange are only marginally adequate. This reflects the non-specificity, ubiquity, and rapid growth of the microbes capable of initiating the process and carrying it forward (18). Second, composting is resistant to outright process failure (24). This stems from the tendency of the climax population, apparently consisting of thermophilic members of the genus Bacillus (44-45) to elevate the temperature to the edge of its tolerance limit (∿ 75°C). In this state decomposition proceeds, but at a mere fraction of the rate achievable at 60°C and less.

This is evidenced herein in that the Rutgers strategy, compared to the Beltsville strategy, induced 3.7x more decomposition and 4.0x more water removal in approximately half the time. This outcome reflects the fundamental difference between these approaches. The Rutgers strategy is to maximize the rate of decomposition through ventilative heat removal in reference to temperature. The Beltsville process, by default, suppresses decomposition through inhibitively high temperature.

The Rutgers strategy is expected to result in more cost-effective composting in terms of facility construction and routine operation. The reasoning is that i. less facility time/space is required, ii. less process residue is produced, decreasing materials handling operations, iii. the residue is easier to handle, store, and transport. Moreover, this strategy improves composting's utility as a waste treatment technology, owing to the production of a process residue that is more amenable to resource recovery/ultimate disposal.

TABLE 7. RECYCLED PROCESS RESIDUE AS BULKING AGENT: AIR USAGE AND MATERIALS BALANCE*

	Pile		
	11A	11B	11C
Period (hr)	0-228	0-186	0-102
Air delivery (m^3/initial wet tonne)			
Total	9,770	10,100	3,370
Mean (hr^{-1})	42.8	54.3	33.1
Peak (hr^{-1})	86.2	119	57.1
Air delivery (ft^3/initial wet ton x 10^3)			
Total	313	323	108
Mean (hr^{-1})	1.37	1.74	1.06
Peak (hr^{-1})	2.76	3.83	1.83
Material decomposed (% of initial dry weight)			
Overall sludge-recycle mixture	24.7	14.8	7.8
Volatile solids	36.4	23.8	13.4
Water removed (% of initial)	85.4	76.1	58.3

[*] Rutgers process control strategy applied to all piles. The calculation is based on the period from time-zero to cessation of temperature feedback control (resumption of timer-scheduled blower operation). Certain entries given in both metric and English units.

SECTION 7

MATHEMATICAL DESCRIPTION OF PROCESS CONTROL DYNAMICS*

In this Section composting process control dynamics are reduced to mathematic form. The mathematical description focuses on the generation and removal of heat; an extra-mathematical constraint is the effect of temperature on heat generation. This development leads to testable predictions of system behavior.

Overall heat removal may be expressed in units of energy/time:

$$Q_t = Q_{conv} + Q_{cond} + Q_r \qquad \text{(i)}$$

where: Q_t = total heat removal

Q_{conv} = convective heat removal

Q_{cond} = conductive heat removal

Q_r = radiant heat removal.

A calculation based on a ventilated field-scale mass indicates that $Q_{cond} \cong 0.02\ Q_t$, and that Q_r is small and sometimes exceeded by radiant gains (4). Thus, all but convective removal may be neglected in the analysis.

The relationship governing convective removal is:

$$Q_{conv} = \underline{m}\ (\underline{h}_{out} - \underline{h}_{in}) \qquad \text{(ii)}$$

where: $\underline{m}$ = dry air mass flow (mass dry air/time)

$\underline{h}_{out}$ = outlet air enthalpy (energy/mass dry air)

$\underline{h}_{in}$ = inlet air enthalpy (energy/mass dry air).

The enthalpy of the air is a function of its temperature and the amount of water vapor it contains. Note that to maintain a quasi-steady state (temperature = constant), Q_t (and hence Q_{conv}) must match heat generation. Note also that the goal is to maximize Q_{conv} in a sustained fashion (quasi-steady state maintained), as this is equivalent to maximizing decomposition rate.

Convective removal can be subdivided into two parts:

$$Q_{conv} = Q_v + Q_{dac} \qquad \text{(iii)}$$

where: Q_v = heat removal through vaporization

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*We thank Dr. Peter F. Strom for helpful discussions on the topics developed in Sections 7 and 8.

Q_{dac} = removal through dry air convection.

At composting temperatures the dominant mechanism of heat removal is vaporization, with $Q_v \overset{\sim}{=} 9\ Q_{dac}$ (2). Removal of heat through vaporization thus can be expressed as:

$$Q_v \overset{\sim}{=} 0.9\ \underline{m}\ (\underline{h}_{out} - \underline{h}_{in}). \tag{iv}$$

Note that the goal of maximizing Q_{conv} pertains equally to Q_v.

The overall rate of water removal is expressed as:

$$\underline{v} = \underline{m}\ (\omega_{out} - \omega_{in}) \tag{v}$$

where: $\underline{v}$ = mass vapor flow (mass moisture/time)

ω = humidity ratio (mass moisture/mass dry air).

With inlet (ambient) conditions of 20°C and 50% relative humidity, approximately 96% of the vaporization is driven by heat generation, and the remainder by inlet air unsaturation (Appendix A-5). Thus we may focus on expression (iv).

The only part of expression (iv) corresponding to a manipulable physical analogue is the coefficient $\underline{m}$, which corresponds to ventilation rate. Thus, $\underline{m}$ represents a means of matching heat removal to heat generation in reference to a constant, activity-promoting, temperature.

Now consider in theory two ways of controlling $\underline{m}$ which predict markedly different behavior patterns (TABLE 8). In the first (see "Prediction" columns), designated R, $\underline{m}$ is varied such that the pile's outlet temperature ascends to 60°C and this value is subsequently maintained as the operational ceiling. The need for a variable $\underline{m}$ stems from the variable rate of heat generation as caused by population shifts, nutrient depletion, available water depletion, and other unidirectional changes characteristic of batch culture. A period of vigorous heat generation ensues, yielding a large Q_v. Consequently the material dries rapidly, ultimately terminating activity for lack of microbially available water (Section 4). The pile is well-oxygenated, as approximately 9-fold more air is needed to remove heat than to supply O_2 for respiration (Appendix D-1).

The second predictive theoretical control approach, designated B, does not involve deliberate temperature management. Rather, $\underline{m}$ is controlled such that interstitial O_2 is not less than 5% (v/v). This is easily accomplished through minimal ventilation on a fixed schedule as it leads, by default, to inhibitively high temperature, suppressing O_2 consumption. Although water removal per unit air is comparatively high (large $\underline{h}_{out}$), owing to a small $\underline{m}$ overall removal (Q_v) is slight. Thus, approach B leads to inhibitively high temperature and a prolonged period of low-level activity. Moreover, attempting to increase Q_v by increasing $\underline{m}$ is not successful. Since heat output is slight, the increased ventilation cools the pile, decreasing $\underline{h}_{out}$.

TABLE 8. BEHAVIOR OF THE COMPOSTING ECOSYSTEM AS INDUCED BY DIFFERENT APPROACHES TO THE CONTROL OF m (VENTILATION MANAGEMENT). PREDICTION BASED ON EXPRESSION iv [$Q_v \cong 0.9\ \underline{m}\ (\underline{h}_{out} - \underline{h}_{in})$], AS CONSTRAINED BY THE INTERACTION BETWEEN HEAT GENERATION AND TEMPERATURE. OBSERVATION BASED ON SIDE-BY-SIDE 36 TONNE PILES (PILES 9A AND 9B).

	Prediction		Observation	
	Approach R[*]	Approach B[†]	Rutgers strategy[*]	Beltsville process[†]
$\underline{m}$ (m^3 air delivered/wet metric ton)				
Total	Large	Small	9660	2350
Peak (hr^{-1})	Peak>mean	Peak=mean	135	6.06[‡]
Mean (hr^{-1})			31.5	4.69[‡]
Temperature (°C)				
Outlet air	60(by design)	80(by default)[§]		
Pile: median (range)			53(24-68)	70(45-82)
Pile: %obs > 60°C (number of obs)			13(1755)	91(1519)
Heat				
Q_v	Large	Small		
$\underline{h}_{out}$ (kj/kg dry air)#	477	1560		
$\underline{h}_{in}$ (kj/kg dry air)$	74.9	74.9		
Decomposition				
Sludge volatile solids decrease (%)	Large	Small	72.3	15.4
Water removal				
Moisture content decrease (%)	Large	Small	67 → 29	65 → 61
Mass H_2O removed (% of initial)	Large	Small	80.9	19.4
kg H_2O/kg dry air	0.1404	0.5394		
kg H_2O/m^3 ambient air			0.0586	0.0793

(continued)

TABLE 8. (continued)

	Prediction		Observation	
	Approach R[*]	Approach B[†]	Rutgers Strategy	Beltsville Process
Processing period (days)	Short	Long	15.8	21
Respiration				
Rate O_2 uptake	High	Low		
O_2 level (% v/v)	High	High	~16%	~16%
CO_2 level (% v/v)	Low	Low	~4%	~4%

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[*] Time-variable, interactive, blower operation (temperature feedback control) in reference to an operational ceiling of 60°C.

[†] Fixed schedule blower operation.

[‡] Difference reflects manual adjustment of schedule (9).

[§] The ecosystem brings itself to the edge of its temperature tolerance limit.

[#] Relative humidity (RH) assumed to be 100%.

[$] Temperature and RH assumed to be 20°C and 50%.

The physical analogues of R and B are the Rutgers and Beltsville approaches, as already compared in detail in previous Sections. In TABLE 8, the comparison is developed in terms of equation (iv). Note that where existing data permit evaluation, prediction is confirmed by observation.

Additional confirmation comes from responses to sudden changes in ventilation. In the Rutgers strategy heat generation is intense, hence accidental loss of blower function is predicted to induce a temperature upsurge. This response was observed numerous times. In the Beltsville process heat generation is weak, hence a sudden increase in ventilation should induce a temperature downturn. Moreover, increased ventilation is not expected to substantially enhance drying, as the decreased $\underline{h}_{out}$ tends to offset the increased $\underline{m}$, moderating any change in $\underline{Q}_v$. This behavior was observed in an unsuccessful attempt to improve drying in field-scale Beltsville piles by increasing ventilation 4-fold partway through the process cycle (10), as described in Appendix D-2.

In the Rutgers strategy the system is not permitted to self-limit via inhibitively high temperature, but rather is prompted to do so via substrate and water depletion. Our experience is that demand for ventilation terminated on day 7.1-15.8 with a mixture of primary sewage sludge and woodchips, and on day 4.3-9.5 with a mixture of the sludge and recycled compost. While the immediate cause of termination was dryness, the addition of water provoked only a weak revival of demand.

Thus, the essence of composting process control is given by the expression $\underline{Q}_v \cong 0.9\ \underline{m}\ (\underline{h}_{out} - \underline{h}_{in})$, as constrained by the interaction between heat generation and temperature. Mathematically, in isolation from this constraint, it might seem that a high value of $\underline{Q}_v$ is obtainable through a high value of $\underline{m}$, or $\underline{h}_{out}$, or both. This is unrealistic however, for two reasons. First, ordinary values of $\underline{h}_{in}$ dictate that an arbitrarily high $\underline{m}$ leads to a low $\underline{h}_{out}$ (see Section 8 - next). Second, values of $\underline{h}_{out}$ representing temperatures higher than 60°C inhibit heat generation. Consequently, the role of $\underline{m}$ is defined as that of matching heat removal to heat generation in reference to temperature, such that maximal sustainable values of $\underline{h}_{out}$ and $\underline{Q}_v$ are realized.

This mathematical development constitutes a formal rationalization for on-demand ventilation via temperature feedback control. This is the basis of the Rutgers strategy for composting process design and control.

SECTION 8

DRYING ASSOCIATED WITH COMPOSTING, AND NON-BIOLOGICAL AIR DRYING

INTRODUCTION

The analysis of Section 7 is extended herein to include the behavior of a biologically inert, ventilated, pile of organic material ("air drying"). This leads to a reinterpretation of the Rutgers and the Beltsville approaches, in a broader context.

THEORETICAL TREATMENT

Simplifying Assumptions

Consider the air drying process as a closed system comprised of a pile (not mechanically agitated) of biologically inert material and the air which is passed through the pile. Neglecting gains and losses of heat through the mechanisms of radiation and conduction, and frictional gains resulting from the passage of air through the matrix, the system (pile and air) experiences no change in enthalpy (= isenthalpic). However, if the inlet air is unsaturated, a redistribution of enthalpy occurs within the system through the vaporization of water from the matrix into the flowing air. This results in a decrease in the enthalpy of the pile exactly balanced by an increase in the enthalpy of the air.

Similarly, consider a static composting pile managed according to the Rutgers strategy and the air passed through it as a closed system, accepting the same simplification with respect to radiant, conductive, and frictional factors. Unlike air drying, the composting system is not isenthalpic; rather, the system's enthalpy increases. This is because chemical bonds are broken through biological action, releasing heat. In common with air drying any unsaturation of the inlet air causes a redistribution of enthalpy. This contributes negligibly to the enthalpy increase of the air, however, compared to biological heat generation.

Two further simplifications are made for the purposes of this exercise. First, the redistribution of enthalpy originating in the unsaturation of the inlet air is neglected. That is, in the air drying examples the air is treated as if it were isenthalpic. Relative to actual conditions this overstates the temperature decrease experienced by the air, and understates the water removal per unit mass of air. It does not affect the composting examples with respect to these factors. Rather, the effect is a small overstatement of the mass of air needed to accomplish a given amount of cooling. These simplifications are adopted to permit the use of standard psychometric data (46).

Next, outlet air RH values must be assigned. For air drying this is not a problem as a necessary condition (short of "breakthrough") is an outlet RH of 100%. For composting an outlet RH of 100% is adopted, in the belief that this is a valid approximation.

Neglect of the enthalpy redistribution originating in unsaturated inlet air introduces a bias favoring composting relative to air drying, with respect to the removal of water per unit mass of air. The stipulation of saturated composting outlet air might introduce a further bias in this direction. We believe that the bias(es) are minor in the context of the exercise, and that the hypothetical examples provide useful approximations of the difference in performance to be expected of air drying and composting, with respect to water removal. Regardless, independent verification based on field data is offered later in this Section.

Hypothetical Examples

As was already seen in Section 7, regardless of whether the driving force is heat generation, unsaturation of the inlet air, or both, vaporization can be described as follows:

$$\underline{v} = \underline{m}\,(\omega_{out} - \omega_{in}) = \underline{m}\,\Delta\omega \qquad \text{(i)}$$

where: $\underline{v}$ = mass vapor flow (mass moisture/time)

$\underline{m}$ = dry air mass flow (mass dry air/time)

ω = humidity ratio (mass moisture/mass dry air)

The outcome of this relationship is exemplified in the non-biological air drying system using various inlet conditions (TABLE 9).

If the inlet air is saturated (e.g. 7.2°C- 100% RH) no change in temperature and RH occurs with passage through the matrix, and no moisture is removed ($\Delta\omega = 0$). If the inlet air RH is less than 100%, water is vaporized from the aqueous matrix into the flowing gaseous phase until an RH of 100% is reached. The vaporization from the matrix causes it to cool, and this is translated into a cooling of the air as its temperature equilibrates with that of the matrix. Thus, in the air drying process the magnitude of moisture removal is solely dependent on inlet air conditions, and the only factor subject to process control is $\underline{m}$. This may be increased to compensate for poor drying air. For example, roughly equal vaporization rates are obtainable with air at 32°C-20% RH or 32°C-90% RH, by using a 10-fold greater $\underline{m}$ for the more humid air.

Heat drying (see last entry in TABLE 9) is a special case of air drying, in which the ambient air is preheated in an operation external to the pile. A gas-fired hot air generator, for example, might be used to condition the inlet air. Compared to the ambient air, this results in a larger $\Delta\omega$.

TABLE 9. HYPOTHETICAL CHANGES IN AIR AS EFFECTED BY THE AIR DRYING PROCESS (BASED ON ISENTHALPIC CONDITIONS - SEE TEXT)*

Process	Inlet air			Inlet and outlet air	Outlet air			
	T (°C)	RH (%)	ω (kg H_2O/ kg dry air)	$\underline{h}$ (kJ/kg dry air)	T (°C)	RH (%)	ω (kg H_2O/ kg dry air)	$v/\underline{m} = \Delta\omega$ (kg H_2O/ kg dry air)
Air drying	4.4	60	.0031	30.2	1.7	100	.0042	.0011
Air drying	7.2	100	.0064	41.2	7.2	100	.0064	0
Air drying	7.2	20	.0012	28.8	0	100	.0038	.0026
Air drying	32	20	.006	65.1	17.3	100	.0123	.0063
Air drying	32	90	.028	121	30.8	100	.0286	.0006
Heat drying†	60	10	.013	111	29.4	100	.026	.0124

* Values of $\underline{h}$ and ω derived from Reference 46.

† The inlet conditions are representative of crpp drying applications (47). Heat drying is a special case of air drying (See text).

Whereas in air drying (and its variant heat drying) the unsaturation of the inlet air is the only force driving vaporization, in composting this factor is minor. Here the major factor is the metabolic generation of heat in the matrix, as follows.

Metabolic activity in the aqueous matrix phase generates heat, establishing an enthalpy differential between the solid-liquid matrix and the gaseous phases (see Section 3). The differential is sustained by the flow, which brings in cooler, drier, air. The differential drives vaporization, and establishes a positive temperature gradient along the axis of airflow. Thus, as long as heat generation persists, the enthalpy of the air increases with passage through the pile. The upper limit to this condition is defined by the heat generation-temperature interaction. The major components of the enthalpy increase are i) an increase in the air temperature, and ii) an increase in the water content per unit mass of air.

Therefore, in composting the rate of vaporization is a function of heat flow. As was derived in Section 7, this leads to the approximation:

$$\underline{Q}_v \cong 0.9\ \underline{m}\ (\underline{h}_{out} - h_{in}) \cong 0.9\ \underline{m}\ \Delta\underline{h} \qquad \text{(ii)}$$

where: $\underline{Q}_v$ = heat flow associated with vaporization (energy/time)

$\underline{h}_{out}$ = outlet air enthalpy (energy/mass dry air)

$\underline{h}_{in}$ = inlet air enthalpy (energy/mass dry air).

An effect of inlet conditions on water removal per unit air during composting is implicit in expression ii, in that ambient temperature and RH determine the value of $\underline{h}_{in}$. (But, variations in $\underline{h}_{in}$ are automatically compensated for in the Rutgers strategy through temperature-feedback adjustment of $\underline{m}$.) The effect of inlet conditions is small, however, as seen in TABLE 10. For example, only 1.2 times as much moisture is removed per unit mass of air by the "best ambient drying air" (7.2°C - 20% RH) than the "worst air" (32°C - 90% RH). This illustrates that, given informed process control, composting process performance is not sensitive to ambient conditions. (Extreme cold is a separate potential problem - see later.)

Thus, the amount of moisture removed per unit mass of air is much greater through composting than air drying. In this hypothetical exercise the amount of water removed through composting is larger by the following factors: 135x, ∞, 58x, 23x, and 207x (compare the $\Delta\omega$'s in TABLES 9 and 10). The factor of infinity is obtained when the inlet air is saturated. Compared to the heat drying example, the composting $\Delta\omega$'s are 10x to 12x greater.

Continuum Among Air Drying, Rutgers Strategy, and Beltsville Process

It is now possible to define the differences among air drying, the Rutgers composting process control strategy, and the Beltsville

TABLE 10. HYPOTHETICAL CHANGES IN AIR AS EFFECTED BY THE COMPOSTING PROCESS*

Inlet air				Outlet air				
T (^{o}C)	RH (%)	h (kJ/kg dry air)	(kg H_2O/ kg dry air)	T† (^{o}C)	RH (%)	h (kJ/kg dry air)	ω (kg H_2O/ kg dry air)	$v/m=\Delta\omega$ (kg H_2O/ kg dry air)
4.4	60	30.2	.0031	60	100	477	.152	.149
7.2	100	41.2	.0064	60	100	477	.152	.146
7.2	20	28.8	.0012	60	100	477	.152	.150
32	20	65.1	.006	60	100	477	.152	.146
32	90	121	.028	60	100	477	.152	.124

* Values of h and ω derived from Reference 46, and where necessary by calculation.

† Based on the outlet temperature characteristic of the Rutgers strategy.

composting process in terms of ventilation. This is done in reference to expression ii. The hypothetical exercise involves a static pile of suitably porous, energy-rich, organic material, different ambient air conditions, and manipulation of m. The constant in expression ii is temperature-dependent and would have to be changed as appropriate, were numerical solutions sought. This is not a source of error in the present qualitative exercise, however, as its outcome is not affected by the value of the constant.

Cases 1 and 2 involve a very high, arbitrary, value of m, such that the material is suspended in the airstream ("fluid bed"). In Case 1 the ambient air (inlet air) temperature is 1°C and its RH is 100%. Because the temperature is biologically unfavorable, heat generation is very slight. Because any heat that is generated is quickly removed, the temperature does not increase to a more favorable level. Consequently, for all practical purposes $Q_v = 0$, and the system's behavior is described by expression i. However v also is zero, as this is the special case of saturated inlet air. Were the RH<100%, evaporative cooling would ensue, v would be greater than zero, and Q_v would be zero.

Case 2 also involves a very high m, but differs in that the ambient air is 30°C-100% RH. Since the temperature favors biological activity heat generation ensues, but the heat is promptly removed and no appreciable temperature elevation results. Nonetheless, the heat generated drives vaporization, $h_{out} > h_{in}$, and the system's behavior is described by expression ii. Although Cases 1 and 2 are of theoretical interest, they would represent extravagant use of energy for ventilation.

Cases 3 and 4 involve composting in the ordinary sense, in that a temperature elevation is experienced. Expression ii pertains in both cases.

Case 3 is that of the Rutgers control strategy, in which the value of m is continuously adjusted through feedback control to seek an outlet temperature of 60°C. Either set of inlet conditions (1°C -100% RH, or 30°C -100% RH) initiates self-heating, although a slow start is experienced with the colder air. Once underway, a quasi steady-state is established in which a sustained high rate of decomposition and vaporization is realized.

Case 4 is that of the Beltsville Process, in which m is set at some low fixed value consistent with the maintenance of a minimal residual O_2 level. This leads to the highest value of h_{out} supportable by the system (but note the low m), and a commensurate inhibitively high temperature (~80°C). Consequently, a quasi steady-state is established characterized by low rates of decomposition and vaporization. This condition is signified by a low Q_v.

FIELD EXPERIMENTATION

Materials and Methods Specific to Section 8

The experimental study concerned a single pile formed of material previously composted by the Rutgers method. This was a mixture of the screened (woodchip-free) material from piles 8 and 9A (Section 3) which had not been used in the 11 series piles (Section 5), and all of the material from piles 11B and 11C. Prior to its use in the present study the material was stored in the open for 3½ to 8½ months. During this period much of it became moist, presumably resulting in further stabilization through informal curing.

This material was formed into a pile of approximately 3.2 tonnes, designated as pile 12. It had a starting moisture content of 65%. The pile was fitted with one blower, thermocouples, and a gas sampling probe (Figure 64). Neither a thermistor nor a timer was required, as the experimental plan called for continuous operation of the blower (100% time on). The forced pressure mode of ventilation was employed. Samples for the determination of moisture content were taken regularly from the part of the pile slightly below that represented by position 5. On some occasions the lower part of the pile represented by position 1 was also sampled.

Time-zero was 27 February 1981 and termination was on 18 March 1981. During this period the ambient temperatures were (°C): mean of the daily highs, 9°; mean of the daily lows, zero°; mean of the daily means, 4.5°; range of the daily highs and lows, -7.8° to 13.9°. Rainfall amounted to 7 cm in four occurrences.

Results

The temperatures of the ambient air and pile position 1 are plotted in the lower graph in Figure 65, and those of positions 1 and 5 are plotted in the upper graph in this figure. (The other temperature data are given in Appendix E.) To help bring out the trends the plotted data are also tabulated in the form of the mean differential values for each 24 hour interval (TABLE 11).

Position 1 tended to be cooler than the ambient air during the first 240 hours, notwithstanding invervals to the contrary (e.g. hr 130 to 160) and intervals of identical temperatures (e.g. hr 180 to 200). Starting at hr 280 position 1 tended to be warmer than the ambient air. Positions 1 and 5 were at similar temperatures during the first 190 hours, and thereafter position 5 was cooler. Position 5 was generally cooler than the ambient air.

The O_2 and CO_2 levels in the pile were not distinguishable from the ambient values.

The moisture content data are given in Figure 66. At the upper sampling level, the moisture content did not change during the experimental period. The lower level experienced a moisture content decrease subsequent to hr 140. At hr 467 an unusually low value (11.2%) was noted.

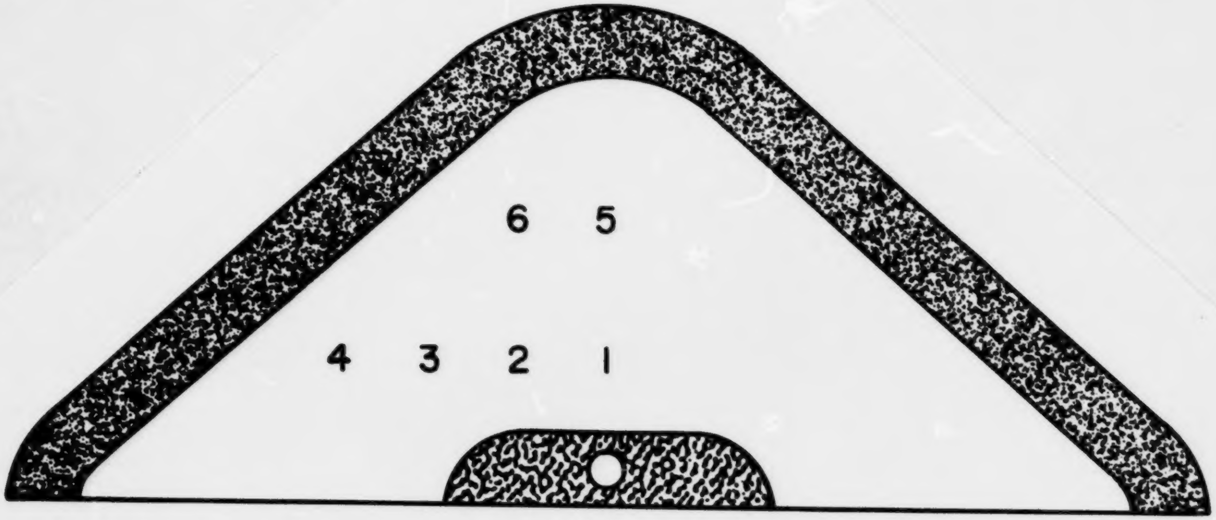

Figure 64. Pile 12, Cross-sectional representation: textured area, woodchip cover and base; clear area, compost; circle, perforated flexhose. The numbers indicate monitoring positions: thermocouples, positions 1 through 6; gas sampling probe, adjacent to position 5. The blower was operated continuously (100% time on) in the forced-pressure mode.

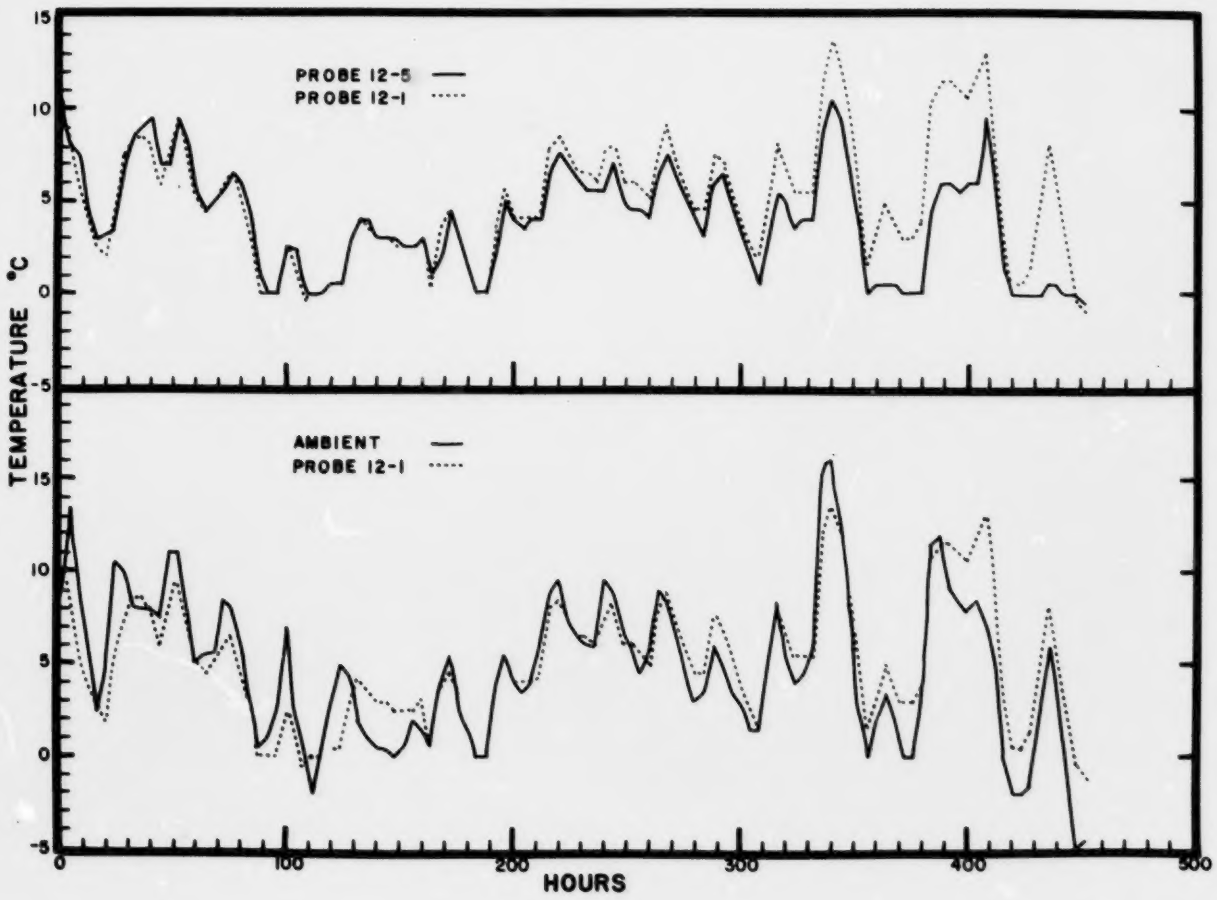

Figure 65. Pile 12, temperature external to the pile (ambient) and at positions 1 and 5.

TABLE 11. TEMPERATURE DIFFERENTIALS AMONG AMBIENT, POSITION 1, AND POSITION 5 PROBES*

Interval (hr)	Position 1 -ambient (°C)	Position 5 -position 1 (°C)	Position 5 -ambient (°C)
0-23	-3	0.6	-2.4
24-47	-1.8	0.2	-1.6
48-71	-1.8	0.7	-1.1
72-95	-1.1	0.7	-0.4
96-119	-0.6	0.2	-0.4
120-143	-0.2	-0.1	-0.3
144-167	1.2	0.1	1.3
168-191	-0.5	0	-0.5
192-215	-0.5	-0.7	-1.2
216-239	-0.4	-0.6	-1.0
240-263	-0.5	-1.1	-1.6
264-287	-0.1	-0.2	-0.3
288-311	1.3	-0.7	0.6
312-335	-0.4	1.1	-1.5
336-359	0.3	-2.4	-2.1
360-383	1.6	-3.4	-1.8
384-407	2.3	-5.3	-3.0
408-431	3.0	-1.4	-1.6
432-455	3.0	-2.8	0.2

*The temperature was recorded every hour. The differential values are based on the mean of the twenty-four hour interval.

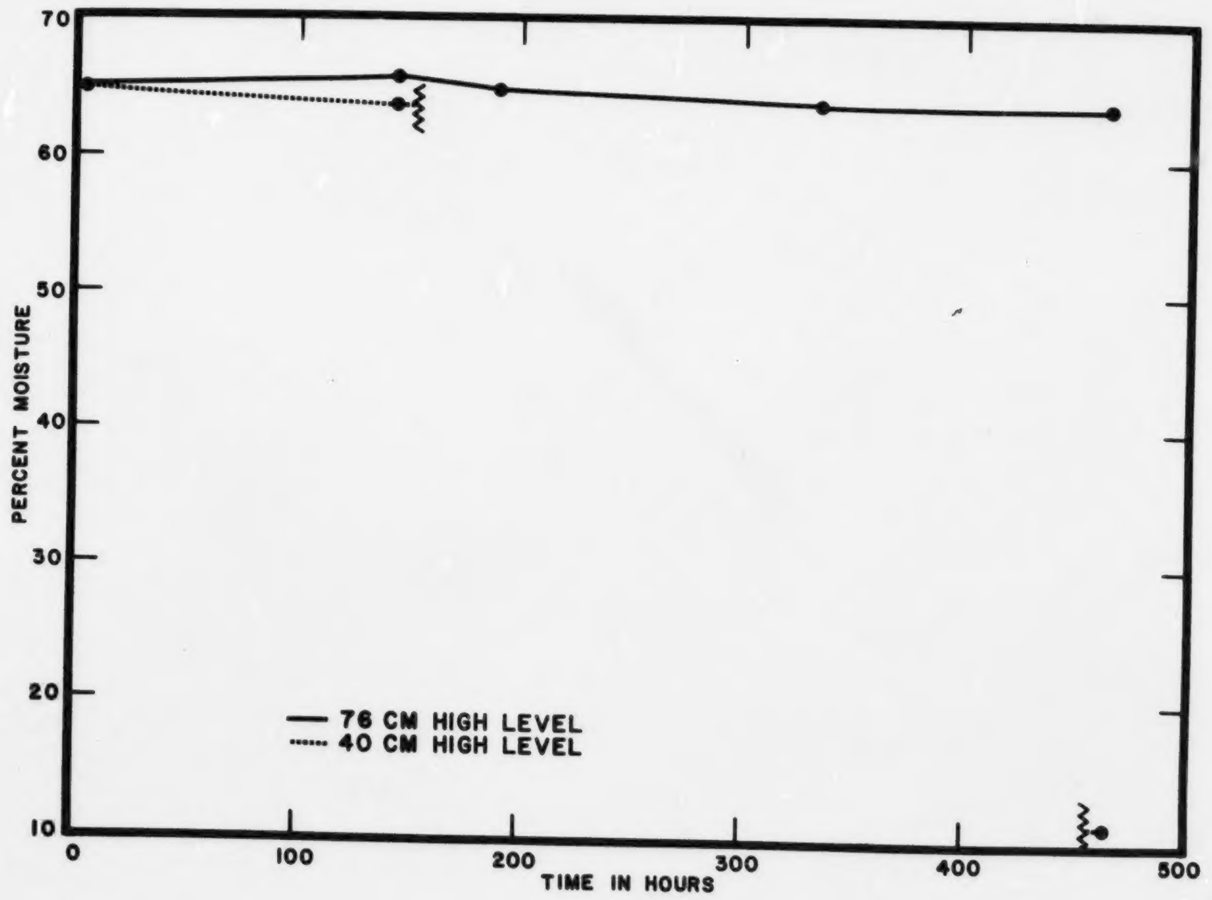

Figure 66. Pile 12, moisture content, samples taken from central interior locations.

At termination the pile was bisected for visual inspection (Figure 67). A hemispherical dry zone, with its origin at the ventilation duct, comprised approximately half the cross-sectional area. This terminated in a 2 cm wide transition zone, evidencing a moisture gradient. The upper half of the cross-sectional area was frankly moist. With respect to other characteristics (granulation, odor, color), the material at termination did not differ noticeably from the starting material.

DISCUSSION

Air Drying

The subject of the experiment was a ventilated pile of compost, as distinct from the usual composting pile. The purpose was to investigate air drying without the complication of biological heat generation. To approach this condition the pile was formed of material previously composted by the Rutgers method, and subsequently cured informally for a prolonged period. As such, the material was depleted of readily metabolizable substrate, and potentially supportive of only slight microbial activity. The timing of the trial was fortuitous in that the ambient air temperature was unfavorably low for microbial activity. Furthermore, the strong ventilation imposed (though not comparable to hypothetical cases 1 and 2) prevented heat storage, which might otherwise have elevated the temperature to a biologically more favorable level. Judging from these conditions and from the pile's behavior as discussed below, heat generation was negligible as intended.

In the virtual absence of heat generation the system is expected to behave as follows. A well-defined cooling-drying front develops at the air inlet point and expands radially along the axis of airflow. Below the front the moisture content of the material comes into equilibrium with the RH of the ambient air; above it the moisture content is unchanged from time-zero. Below the front the temperature of the material and interstitial air is at the ambient level (except for frictional heat input - see later); above it the temperature is less than ambient.

This behavior is predicted because the drying and cooling both result from vaporization — driven solely by unsaturation of the inlet air. In this circumstance the unsaturated condition is abruptly terminated through the action of two complimentary forces at the drying-cooling front: 1) the transfer of moisture into the gaseous phase, saturating it, and 2) the cooling of the gaseous phase as it comes into temperature equilibrium with the matrix, decreasing its capacity to hold moisture at saturation. In combination, these forces bring vaporization and cooling to a sharp halt, hence a narrow, well-defined front. This cooling-drying front migrates through the pile with time, leaving in its wake an expanding region of air-dried material. The material ahead of the front is undried.

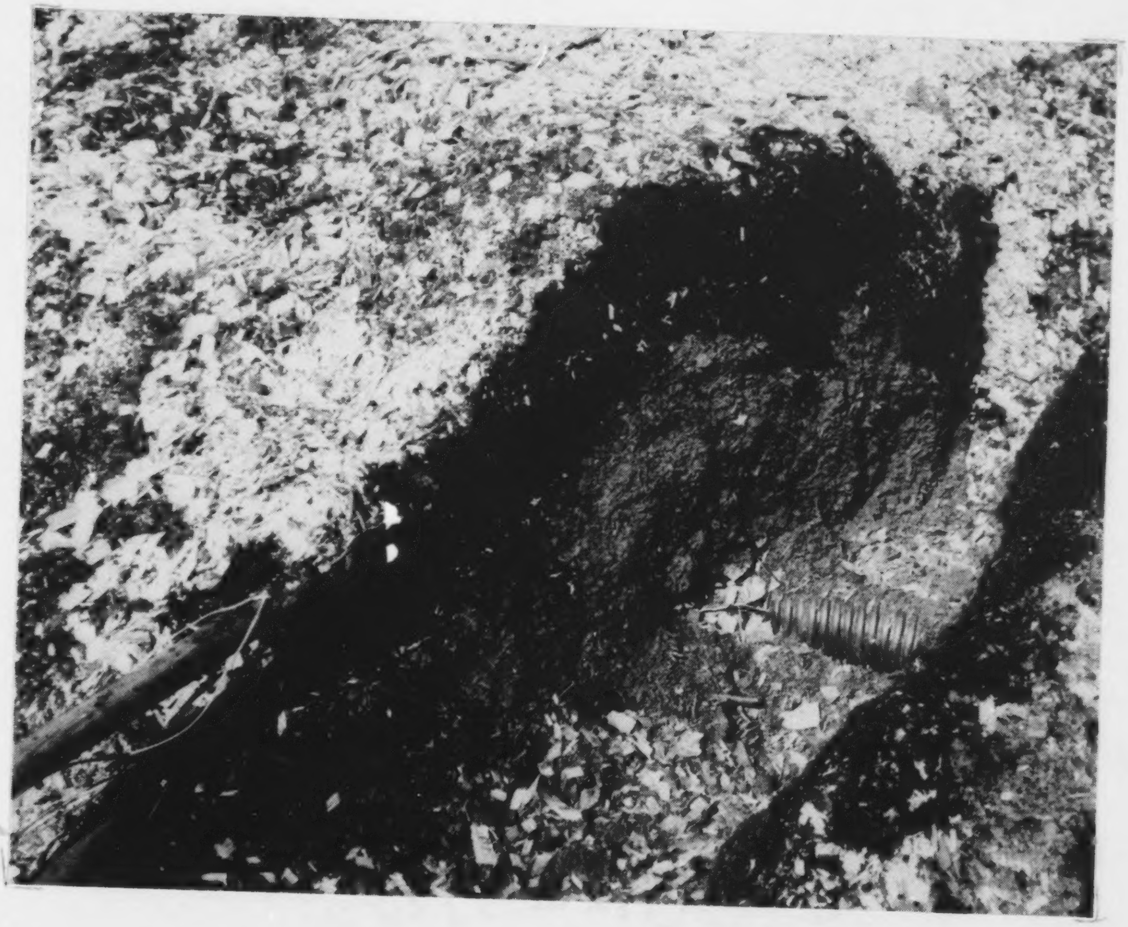

Figure 67. Pile 12, cross-section at termination. Note boundary between moist upper area and dry lower area. Photo by F.C. Miller.

These predictions were verified in the experimental observations. Cooling is evident in the temperature differentials between: position 1 and ambient; position 5 and 1; positions 5 and ambient. The pattern of the differentials is suggestive of a cooling front passing position 1 roughly midway through the experimental time period, but not reaching position 5 by termination. This is inferred from the sign change, from negative to positive, in the differential between position 1 and the ambient temperature, and the opposite change in the differential between positions 5 and 1. Thus the temperature decreased and the decrease was discontinuous, as expected of a system in which biological heat generation is negligible.

In stipulating isenthalpic air in the hypothetical air drying example, it was noted that this exaggerates the temperature decrease (see Simplifying Assumptions). This is because the exercise is based on standard psychometric data, which do not take into account the interaction between the gaseous phase and the liquid-solid phase (the air is cooled by the matrix). Additionally there is a second source of error in the same direction, in the form of frictional heat input, resulting from the forcing of the air through the matrix. In the virtual absence of biological heat generation, frictional heat could be significant. Neither of these errors can be quantified at present.

It is possible to develop an exercise, not without its own difficulties, comparing the theoretical isenthalpic cooling and the observed cooling. The exercise is as follows.

During the experimental period the mean ambient temperature (mean of the daily means) was 4.5°C. Relative humidity was not measured, and the ambient value no doubt fluctuated widely. Nevertheless, if an RH of 60% is taken as a representative ambient value, and if inlet conditions were constant at 4.5°C - 60% RH, an isenthalpic temperature decrease of 2.5°C is predicted. The data offer three opportunities for comparison to the hypothetical value, as follows: position 1 minus ambient, from time-zero to hr 215; position 5 minus position 1, from hr 216 to termination; position 5 minus ambient, for the entire period. The observed mean differentials are, respectively, (°C): -0.8, -1.9 and -1.0. Thus observation conforms to theory in that the means of the data are negative, and the absolute values are less than 2.5.

Starting at hr 280, above-ambient temperatures were noted at position 1 (TABLE 11). This is attributed to frictional heat input.

Thus, despite the complications inherent to this exercise, the temperature data are suggestive of the migration of a cooling front through the pile.

The moisture content data provide equally suggestive data for the drying component of a cooling-drying front (Figure 66).

Perhaps the most compelling evidence, however, is in the form of the visual appearance at termination (Figure 67). This revealed unambiguously that a distinct, radial, drying front had indeed passed position 1 but had not reached position 5. It is concluded that the observations are as predicted by the model of the non-biological air drying process (expression i).

Water Removal: Operational Implications

Water removal per se is a goal in sewage sludge treatment. It is therefore of interest to compare composting and air drying from this narrow perspective. This comparison neglects the other treatment goals advanced through composting.

Consider the two approaches to composting. In the Rutgers strategy, one-third less water was removed per unit air delivery. This reflects the characteristically lower value of h_{out}. However, owing to the high proportion of water removed and the speed of its removal, only the Rutgers strategy affords a useful means of drying sludge. (Also, see Appendix D-2).

Compared to non-biological air drying, the biological system (Rutgers strategy) removed 22.3x more water per unit air delivered. This reflects the dominant role in composting of heat as the force driving vaporization. Unsaturation of the inlet air plays only a minor role. In air drying, however, inlet air unsaturation is the only operative mechanism. In addition to its efficiency in terms of air usage, composting removes a higher proportion of the water, and the removal is faster. This comparison is expressed in terms of the cost of pumping air (TABLE 12.)

TABLE 12. COST OF WATER REMOVAL THROUGH BIOLOGICAL AND NON-BIOLOGICAL MEANS

Process	Water removed/ unit air delivered (ton x 10^{-6}/ft^3	Processing time (days)	Proportion of initial water removed (%)	Cost of air delivery/unit water removed ($/ton)[§]
Composting-Rutgers strategy[*]	1.85	9.8	75.7	0.31
Composting-Beltsville process[†]	2.48	20.8	19.4	0.21
Non-biological air drying[‡]	0.0828	18.8	46.7	6.33

[*] Based on piles 7, 8, 9A, 11A, 11B, 11C.

[†] Based on pile 9B.

[‡] Based on pile 12; assumes that half the material was air dried at termination, and half unchanged from initial moisture content (see Figures 66 and 67).

[§] Based on electricity @ $0.06/kw-hr.

SECTION 9

COMPARISON BETWEEN THE RUTGERS AND BELTSVILLE CONTROL STRATEGIES: EFFECT ON CURING STAGE

INTRODUCTION

The greatest benefit from formal process control is realized early in the composting, when readily metabolizable organic substrates are most abundant and the potential for decomposition is greatest. As readily available substrate is depleted it becomes feasible to continue the processing, if necessary to do so, on a less formal basis. The earlier period may be called the high rate stage, and the later period the curing stage.

The present section concerns the curing of materials previously composted by the Rutgers and Beltsville methods.

MATERIALS AND METHODS SPECIFIC TO SECTION 9

Material from piles 9A and 9B (Section 3) was screened, to remove woodchips, with a Royer Model 365 shredder/mixer, coupled with a Mogensen sizer (Royer Foundry and Machine Co., Kingston, PA). Screened material was transported from the primary composting site at Camden, N.J. to New Brunswick, N.J., to form two separate curing piles. Each pile consisted of approximately 3m^3 of material in a conical shape. A stainless steel dial thermometer of 1 meter length was inserted into the center of each pile, where it remained throughout the trial. The experimental chronology and related matters are given in TABLES 13 and 14.

On two occasions the piles were remoistened with water from a garden hose. As part of this operation the material was turned and mixed by shovel.

Samples were removed periodically from the pile interior and tested qualitatively for NH_4^+, NO_2^-, and NO_3^-. The reagents were as described in Standard Methods under items 132B and 134 (48). Devardas alloy was used as a reductant in the test for NO_3^-.

Samples from the pile interior were subjected to an odor test on the day of sampling. The material was placed into 1 pint (ca.0.5ℓ) screw-cap jars, such that they were one-third full. The jars were coded to conceal sample identity, and randomly selected individuals (excluding project personnel) were asked to evaluate the samples on a scale of -5 to +5 (-5 = most unpleasant; 0 = neutral; +5 = most pleasant). Twenty people evaluated the first set of samples, and 38 people the second set.

TABLE 13. PERTINENT DATES, ELAPSED TIME, AND WEATHER

- Time zero (parent pile formation)[*]
  - Rutgers: 9 Jul 1980
  - Beltsville: 11 Jul 1980
- Parent pile screening[*]
  - Rutgers: day 36
  - Beltsville: day 26
- Curing pile formation[†]
  - Rutgers: day 40
  - Beltsville: day 26
- Termination (10 Nov 1980)
  - Rutgers: day 124
  - Beltsville: day 122
- Weather (1 Aug to 10 Nov)[‡]
  - Ambient air temperature (°C)[§]
    - High: 25
    - Low: 14
    - Mean: 20
    - Range: -5 to 37
  - Rainfall
    - Amount (cm): 21.6
    - Occurrences (no.): 15

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[*] At Camden, N.J.

[†] At New Brunswick, N.J.

[‡] This is taken to represent the conditions following the start of the curing stage. See Table 2 for conditions during the high rate stage.

[§] High = mean of the daily highs; low = mean of the daily lows; mean = mean of the daily means; range = overall range of the daily highs and lows.

TABLE 14. MANIPULATIONS OF THE CURING PILES, AND CHARACTER OF THE MATERIAL

Moisture content (%) and water addition*

- Rutgers parent pile: day 0 to 19, see Figure 36; day 24, 25%
- Rutgers curing pile: day 76, water added; day 84, water added; day 90, 63%; day 107, 64%
- Beltsville parent pile: day 0 to 21, see Figure 36; day 22, 65%
- Beltsville curing pile: day 74, water added; day 82, water added; day 88, 58%; day 105, 53%

Odor test (mean score)

- Rutgers curing pile: day 86, - 1.30; day 91, + 0.66
- Beltsville curing pile: day 84, - 3.15; day 89, - 2.29

First detection of NO_2^-

- Rutgers curing pile: day 86
- Beltsville curing pile: day 113

First detection of NO_3^-

- Rutgers curing pile: day 99
- Beltsville curing pile: day 123

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*The piles were turned as part of the water addition operation.

RESULTS

Because of its physical accessibility the parent Beltsville pile (9B) was screened first, permitting the earlier formation of its derivative curing pile (TABLE 13). This curing pile was moist from the outset (see Figure 68 and TABLE 14). A subsequent period of rainfall delayed the screening of the Rutgers pile (9A), but the material eventually obtained was from the interior of the pile (unaffected by the rain). Hence this derivative curing pile was dry at the outset (Figure 36 and TABLE 14). In addition to the moisture content data, the dry condition of this curing pile over much of the trial was indicated by visual and tactile examination of the samples obtained periodically for the nitrogen spot tests. On day 76 the material was wetted by the addition of water and turning.

The Rutgers curing pile cooled more quickly and in a more regular pattern than its Beltsville counterpart (Figure 68). In the Rutgers pile a slight, temporary, temperature descent coincided with the first water addition-turning operation (day 76), but not the second such operation. In the Beltsville pile sharp descents and re-ascents coincided with both addition-turning operations.

Based on the average test panel score, at the time of the first odor test the material from the Rutgers curing pile was less unpleasant than the Beltsville material (TABLE 14). At the time of the second odor test the freshly sampled material from the Rutgers pile was rated at the low end of the "pleasant" range. Although the material from the Beltsville pile was improved with respect to odor, it still was considered distinctly "unpleasant."

The end products of both steps of nitrification (NO_2^- and NO_3^-) appeared earlier in the Rutgers pile (TABLE 14).

DISCUSSION

In the parent pile 9A there was intensive heat generation (decomposition) and vaporization, hence the derivative curing pile was formed of moderately well-stabilized, dry, material (TABLE 14). Because of the dryness, activity was probably slight from approximately day 15 to day 76 (when the material was wetted). Thus, dryness presumably delayed curing by as much as two months. In routine operation timely water addition would be indicated to prevent a curing hiatus.

In contrast, parent pile 9B experienced inhibitively high temperatures, with correspondingly slight decomposition and vaporization. Its derivative curing pile was formed of poorly stabilized, moist, material. Although direct observations are lacking, we suspect that activity in this pile was O_2-limited for a part of the curing period.

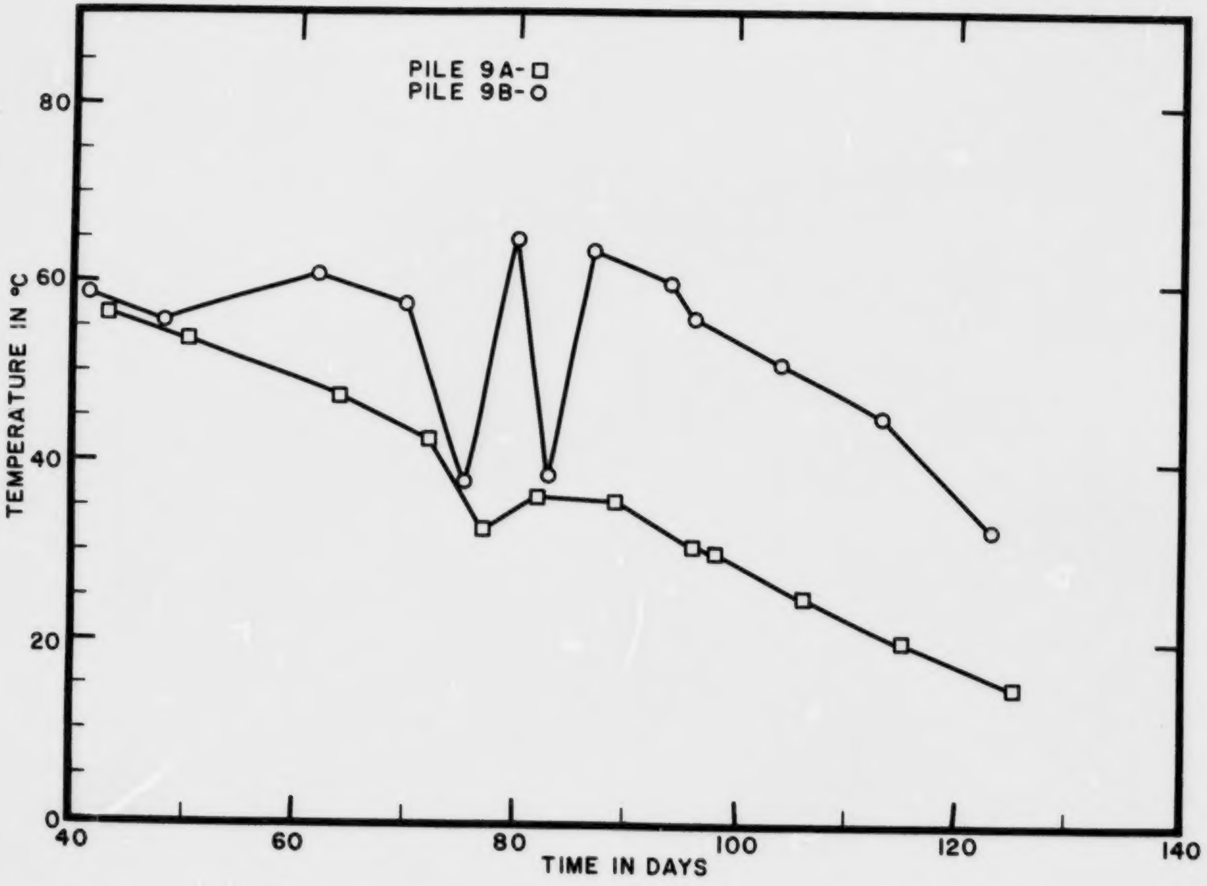

Figure 68. Curing piles, temperature in the center of the pile.

The circumstances at the start of the curing period may be summarized as follows. The material derived from pile 9A was ready for curing, as it had reached a moderately well-stabilized condition. Curing was delayed, however, by dryness. The material derived from pile 9B was not ready for curing, as prior stabilization was slight.

Despite the dryness-induced curing hiatus, 9A material was first to reach a well-cured condition judging by the cooling rate, odor, and onset of nitrification. (Although cooling is generally a sign of substrate depletion, in the present case the issue is clouded by the effect of the dryness on biological heat generation.) Odor is of obvious practical operational interest, as well as being indicative of the degree of stabilization. This odor test result is consistent with other formal observations on odor (2, 29).

The validity of nitrification as a sign of organic matter stability is widely appreciated in the sewage treatment field, among other fields (49). This stems from several characteristics of the responsible bacteria, such as their chemoautotrophic nature, sensitivity to elevated temperatures, and slow growth.

In routine practice the addition of water could be made part of the transferral operation from the site of the high rate operation to the curing site. Alternatively, water might be added during the high rate stage, as needed to sustain microbial action. In this manner the high rate stage would pass to the curing stage without moving the material. This mode of operation can be visualized by reference to Figure 42.

In designing a water addition program, it should be recognized that the material becomes progressively more difficult to wet as it dries. As a rough approximation, it might be advisable to add water as the moisture content decreases to perhaps 40%.

In employing composting as a waste treatment technology it is generally desireable, in the initial processing, to strive for a maximal decomposition rate. Whether it is necessary to subsequently cure the material is a site-specific matter. This depends on the nature of the waste and the intended avenue of ultimate disposal/resource-recovery.

SECTION 10

RUTGERS CONTROL STRATEGY: DIAGNOSIS OF PROCESSING FAILURE

INTRODUCTION

The original intent of this trial was to examine the effect of wetness on composting by the Rutgers strategy, by isolating starting moisture content as the variable. One batch of sludge cake and woodchips was mixed without addition of water, to serve as the control, while water was added to two batches. During composting, however, all three piles behaved similarly, exhibiting inhibitively high temperatures, low rates of activity and decomposition, and slight drying. These patterns indicated processing failure by the standards of the Rutgers strategy.

The suspected immediate cause of failure was inadequate penetration of air into the composting mass, leading to inadequate heat removal. Both a low amount of bulking agent in the mix, and an overly large woodchip ventilation base contributed to poor air penetration. This outcome, though, lead to an unplanned interpretative opportunity to contrast the behavior of a failed pile with that of a successful one from a different trial.

MATERIALS AND METHODS SPECIFIC TO SECTION 10

Each pile consisted of approximately 6 tonnes of the sludge-woodchip mixture (excluding added water). Pile 6A was formed using unammended sludge cake and woodchips (no water added). For pile 6B tap water was added from a garden hose at a "moderate rate" as the sludge and woodchips were mixed in the pug mill, and for pile 6C the rate of addition was "fast." The ratio of sludge to woodchips was the same in all piles (1 tonne sludge to 1.35m^3 woodchips). The added water is not taken into account in this ratio. The controller set point for all of the piles was 45°C.

The trial period was 13 March 1980 to 3 April 1980. Ambient air temperatures during this period were (°C): mean of the daily highs, 13; mean of the daily lows, 2; mean of the daily means, 11; range of the daily highs and lows, -3 to 20. Precipitation amounted to 14.4 cm in 12 occurrences.

In a special terminal test (3 April) of the penetration of air into the sludge-woodchip mixture of pile 6B, hot air was substituted for ambient air by use of a kerosene-fired catalytic space heater rated at 24 x 10^{6}gm cal/hr (95,000 btu/hr). The heated air was introduced to the inlet of the blower, which resulted in air at 130°C being introduced to the flexhose. Prior to the start of this test five additional thermocouples were positioned at 0.3m intervals in the woodchip base midway between the top and bottom of the base, in a line perpendicular to the flexhose.

RESULTS

All three piles failed. One of these (6B) is compared to a previously described successful pile of comparable size (pile 7 - see Section 3). Certain details not included herein are recorded in Section 3, Appendices A-1 and A-2, and Appendix F. Piles 6B and 7 are shown in cross-section (Figure 69).

Blower Operation

For pile 6B the period of timer-scheduled operation lasted until hr 138, at which point temperature-feedback control came into play (Figure 70). Blower operation was demanded for 100% of the time, and the demand did not subside.

For pile 7 the initial timer period lasted until hr 56, followed by feedback control. Demand built to a peak of 65%, at hr 110, then gradually subsided. Demand terminated at hr 344, with the resumption of timer-scheduled operation.

Temperature

In pile 6B the time-zero temperature was 8-11°C (Figure 71). At most of the positions the temperature ascended gradually, though at an accelerating rate, so that at the control thermistor (position 1) 138 hours elapsed before reaching set-point (45°C). The temperature pattern at some of the outermost positions was erratic. Feedback control did *not* arrest the temperature ascent. Whereas the temperature at the thermistor should have stabilized at 45°C, it did so at 68°C. Elsewhere, higher temperatures generally prevailed.

In pile 7 the time-zero temperature was 18-22°C. The temperature ascended faster, such that at the control thermistor (position 6) 56 hours elapsed before reaching set-point (45°C). The onset of temperature feedback control arrested the ascent at the thermistor at 45°C, and elsewhere the design ceiling of 60°C was rarely exceeded.

Oxygen

In pile 6B the lowest O_2 level observed was 10% (Figure 72). The comparable observation for pile 7 was 14%. Thus, in both piles oxygenated conditions were maintained.

Moisture Content

In pile 6B the moisture content decreased from 72% to 68% (Figure 72). The comparable decrease in pile 7 was from 62% to 28%. Thus, the drying tendency was strongly expressed only in pile 7.

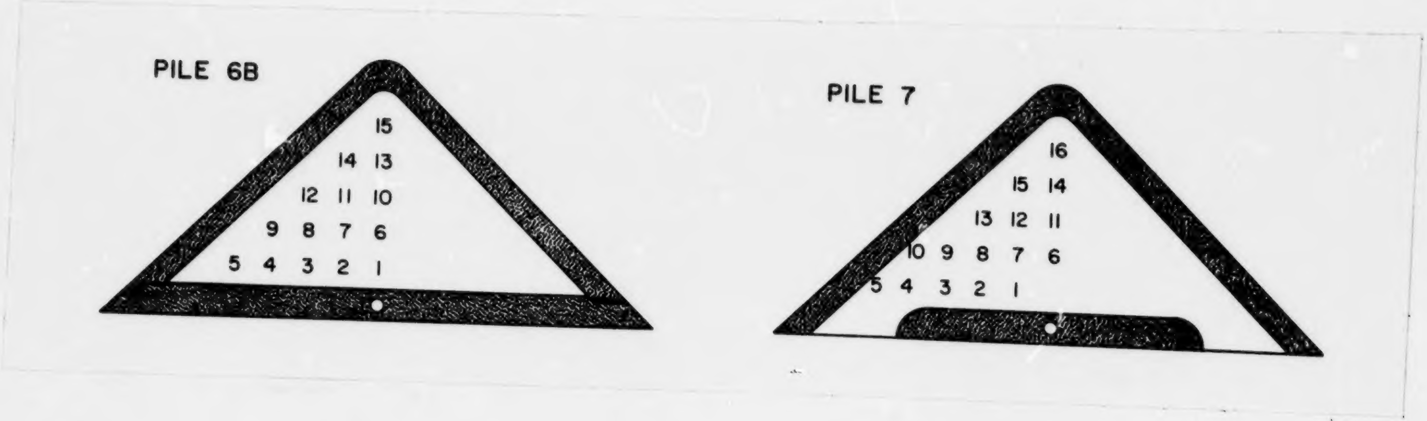
PILE 6B
15
14 13
12 11 10
9 8 7 6
5 4 3 2 1
PILE 7
16
15 14
13 12 11
10 9 8 7 6
5 4 3 2 1

Figure 69. Cross-sectional representation of piles 6B and 7 (see also Section 3). Textured area, woodchip cover and base; clear area, sludge-woodchip mixture; circles, perforated flexhose; positions 1-16, thermocouples in a 0.3 m x 0.3 m grid. In pile 6B the thermistor was at position 1, and in pile 7 it was at position 6. The woodchip base dimensions (L x W x H) were: pile 6B, 5.2 m x 4.6 m x 25 cm; pile 7, 3.1 m x 2.7 m x 25 cm. The bottom-most level of the sludge-woodchip mixture had areal dimensions (L x W) of 4.9 m x 4.3 m (both piles). The piles were slightly longer in the axis parallel to the flexhose than in cross-section.

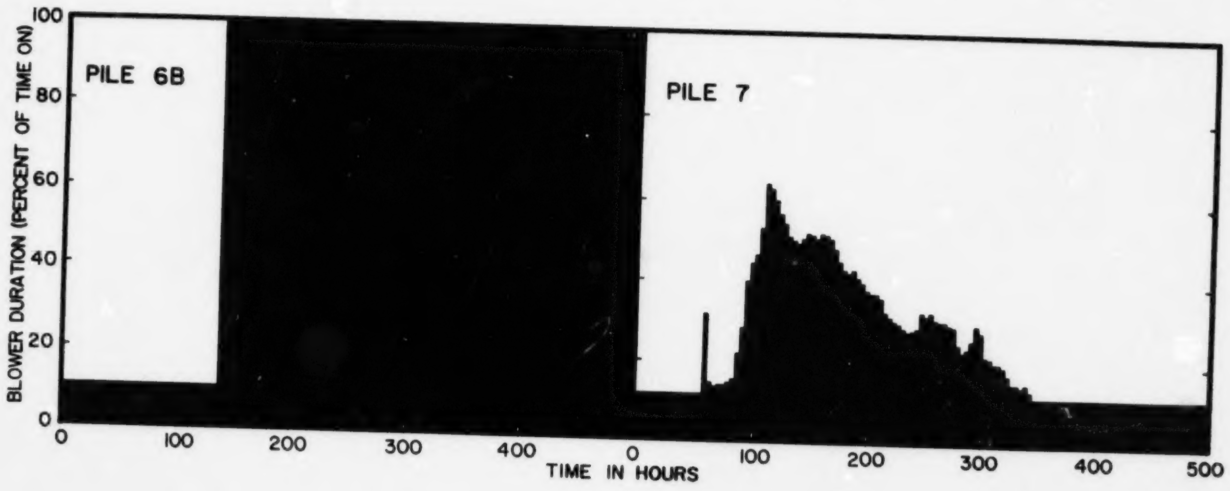

Figure 70. Reprinted by permission from TOXIC AND HAZARDOUS WASTE: Proceedings of the 15th Mid-Atlantic Conference, pp. 463-471. Copyright c 1983. Bucknell University Blower operation, mean of four hour intervals (see also Section 3).

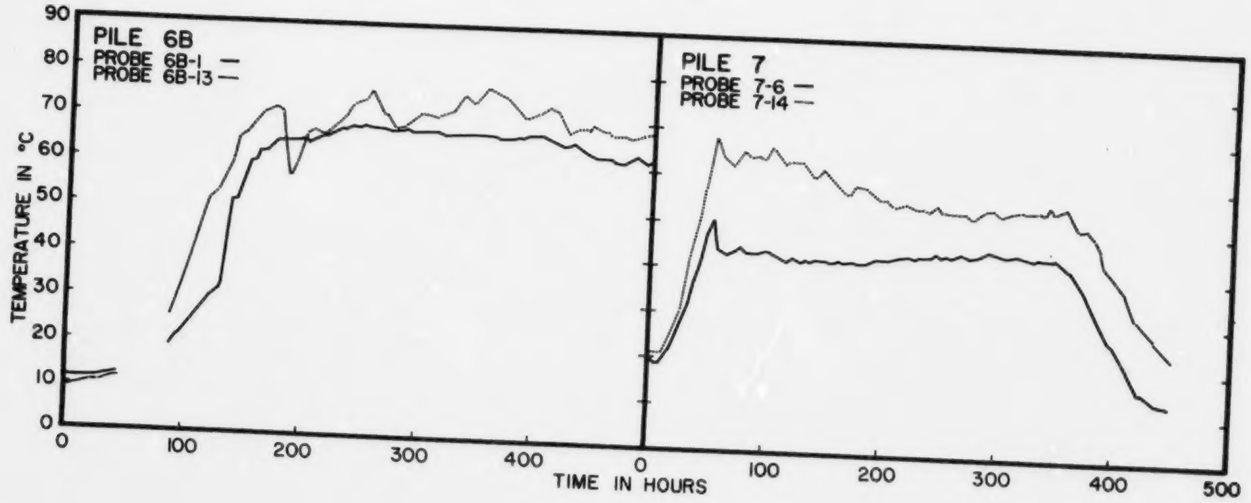

Figure 71. Reprinted by permission from TOXIC AND HAZARDOUS WASTE: Proceedings of the 15th Mid-Atlantic Conference, pp. 463-471. Copyright c 1983. Bucknell University. Pile temperature at selected interior positions, plotted every four hours. Control thermistors were at positions 6B-1 and 7-6 (see also Section 3).

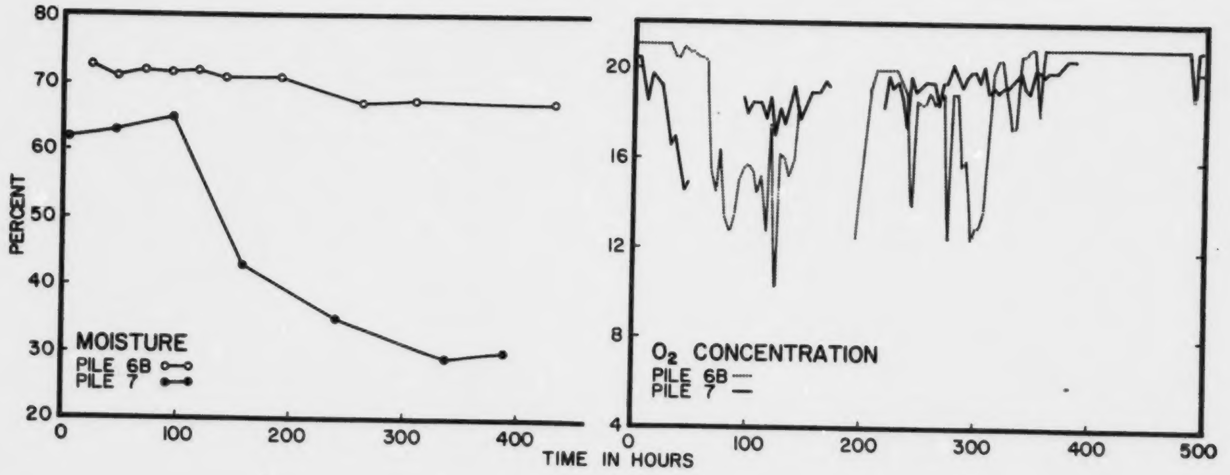

Figure 72. Reprinted by permission from TOXIC AND HAZARDOUS WASTE: Proceedings of the 15th Mid-Atlantic Conference, pp. 463-471. Copyright c 1983. Bucknell University. Left, moisture content of samples taken from the pile interior (see also Section 3.) Right, concentration of O_2 (v:v) in gas samples taken at four hour intervals. Sampling probes were at position 13^2 (pile 6B) and position 6 (pile 7).

Diagnosis

With the recognition that pile 6B failed, an effort was made to diagnose the responsible operational flaw(s). The suspected immediate cause of failure was inadequate penetration of air into the mass, leading to inadequate heat removal. The extent of air penetration was tested, on day 20, with the use of externally heated air (130°C measured in the flexhose duct between blower and pile).

Thirty minutes of continuous input of heated air resulted in a 33.8°C temperature elevation in the woodchip base at the monitoring position nearest the flexhose, and a 10.3 C elevation at the furthest base position (Figure 73). The maximum elevation in the sludge-woodchip mixture itself (1.1°C) was immediately above the flexhose. This indicates that most of the air passed horizontally through the woodchip base, rather than passing up through the sludge-woodchip mixture.

DISCUSSION

Two of the factors influencing air penetration into the composting mass are the porosity of the sludge-bulking agent mixture, and the design of the woodchip base. Porosity is affected by the sludge-bulking agent ratio and by the moisture content, among other factors. Both insufficient porosity and poor base design probably contributed to the failure of pile B.

In routine practice, the more favorable porosity represented by pile 7's sludge: bulking agent ratio and initial moisture content should be an operational goal. However, variations in porosity are unavoidable. In contrast, woodchip base construction is repeatable without variation, and its design should be optimized. The base design represented by pile 7 is superior in that it suppresses short-circuiting, directing the air to the overlying mass.

One aspect of the comparative performance of these piles is explained by ambient temperature. This is the length of time needed to reach the set-point temperature, which was 2.5x lengthier for pile 6B than pile 7. The lengthier "come-up" is attributable to the lower, biologically unfavorable, time-zero ambient temperature. The explanation of the other performance aspects resides in the factors governing the composting ecosystem, as influenced by feedback ventilation control.

With adequate air penetration, represented by pile 7, demand for heat removal is met via blower operation. This induces an interaction between pile and blower manifested in time-variable blower operation, leading to the regulation of pile temperature. This results in rapid decomposition, rapid drying, and an oxygenated condition. The first two factors are intimately linked, in that decomposition generates heat - which vaporizes the water. The oxygenated condition reflects the balance between a high rate of oxygen consumption and a commensurately high rate of oxygen resupply.

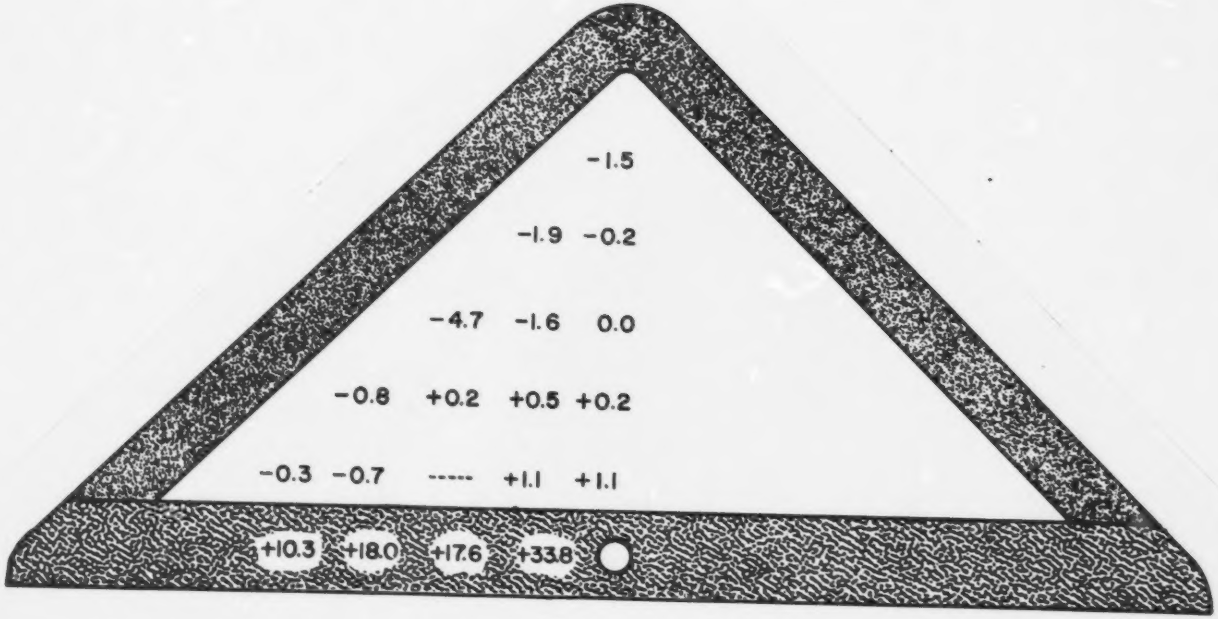
-1.5
-1.9 -0.2
-4.7 -1.6 0.0
-0.8 +0.2 +0.5 +0.2
-0.3 -0.7 ----- +1.1 +1.1
+10.3 +18.0 +17.6 +33.8

Figure 73. Reprinted by permission from TOXIC AND HAZARDOUS WASTE: Proceedings of the 15th Mid-Atlantic Conference, pp. 463-471. Copyright c 1983. Bucknell University. Pile 6B; temperature changes after 30 minutes continuous input of externally heated air.

Non-adequate air penetration, represented by pile 6B, unlinks blower demand and heat removal, in that the air (or much of it) is short-circuited. Hence, pile and blower do not interact. The consequent failure to arrest the temperature ascent leads to inhibitive levels; consequently, decomposition and drying are slight. An oxygenated condition prevails, because the slight rate of oxygen resupply suffices to roughly match the slight rate of consumption.

Finally, these observations are put into a broader perspective by comparing the nominal behavior of a composting pile managed according to the Rutgers strategy (e.g. pile 7), the nominal behavior of a Beltsville-type pile (e.g. pile 9B), and a failed pile intended as a Rutgers pile (6B) (TABLE 15). Nominal Rutgers behavior requires a ventilation system adequate in three respects. First, the blower must respond, in a time-variable fashion, to the need for heat removal in reference to temperature (temperature-feedback control). Second, the blower must be adequately sized, to meet the peak demand for ventilation. Third, the air must pass through the mass reasonably freely. The system represented by pile 7 was adequate with respect to all three factors; the pile 6B system was deficient with respect to the third factor; the pile 9B system was deficient with respect to the first and second factors.

Thus, piles 6B and 9B had different deficiencies in terms of their ventilation systems. The outcome was similar, however, in that excessive heat accumulation was manifested in inhibitively high temperature coupled with a high level of 0_2. This demonstrates that a processing failure by Rutgers standards resembles nominal performance by Beltsville standards.

TABLE 15. NOMINAL AND FAILED BEHAVIOR OF COMPOSTING SYSTEMS

	Nominal behavior		Failed behavior
	Rutgers	Beltsville	Rutgers
Temperature	Regulated, as intended	Regulation not attempted, inhibitively high	Regulation failed, inhibitively high
Drying tendency	Strong	Weak	Nil
Demand for ventilation	Builds gradually to peak	N/A	Built instantaneously to peak
Level of peak demand	Usually <100%	N/A	100%
Duration of peak demand	Hours or days, then dwindles	N/A	Sustained indefinitely
Interstitial atmosphere	Oxygenated*	Oxygenated†	Oxygenated†
Temperature gradient	Decisively established	Weakly established	Weakly established

*Result of rapid O_2 uptake balanced by rapid resupply (see Section 3).

†Result of slow O_2 uptake balanced by slow resupply (see Section 3).

SECTION 11

PATHOGEN INACTIVATION

INTRODUCTION

Composting can serve as a waste treatment technology owing to its capacity to stabilize and sanitize the material. The components of stabilization are the decomposition of putrescible matter, the reduction of volume and weight, and the removal of the water. All of these are advanced through maximization of the rate of decomposition. The material is sanitized through biological antagonisms that inactivate or destroy pathogenic organisms, and through temperature-inactivation. Biological antagonisms, though poorly understood, are presumably also promoted through maximization of the decomposition rate, as this is synonymous with the general level of biological activity. To this extent, therefore, the goals of stabilization and sanitation are advanced in tandem. With respect to temperature-inactivation, however, a potential for conflict exists. Inactivation through this mechanism is positively related to temperature throughout the range of possible composting temperatures (peak ≅ 80°C), whereas the threshold to a significant decrease in decomposition rate is approximately 55°-60°C.

This potential conflict would be aggravated by an administrative regulation calling for "the fastest possible pathogen inactivation" (15). A regulation so worded would mandate the earliest possible attainment of the highest possible temperature. However, the Federal interim final criteria for pathogen reduction (50) are worded in a manner that permits a degree of operational flexibility in meeting the indicated goals. The criteria are for "significant pathogen reduction" (at least 40°C for 120 consecutive hrs and, within this period, at least 55°C for 4 hrs), and "further pathogen reduction" (at least 55°C for 72 consecutive hrs).

These criteria can be met with little or no penalty in terms of stabilization and water removal through tactics involving either the high rate stage or the curing stage. The former is demonstrated experimentally in the present section; the latter is noted in discussing the problem of monitoring regulatory compliance.

MATERIALS AND METHODS SPECIFIC TO THIS SECTION

The trial involved a 6 tonne pile of the sludge-woodchip mixture (pile 13). In addition to the usual thermocouple grid in the mixture, four thermocouples were positioned in the woodchip bed (Figure 74). (Note that the mixture was accidentally placed in an off-center orientation relative to the flexhose duct.) The controller

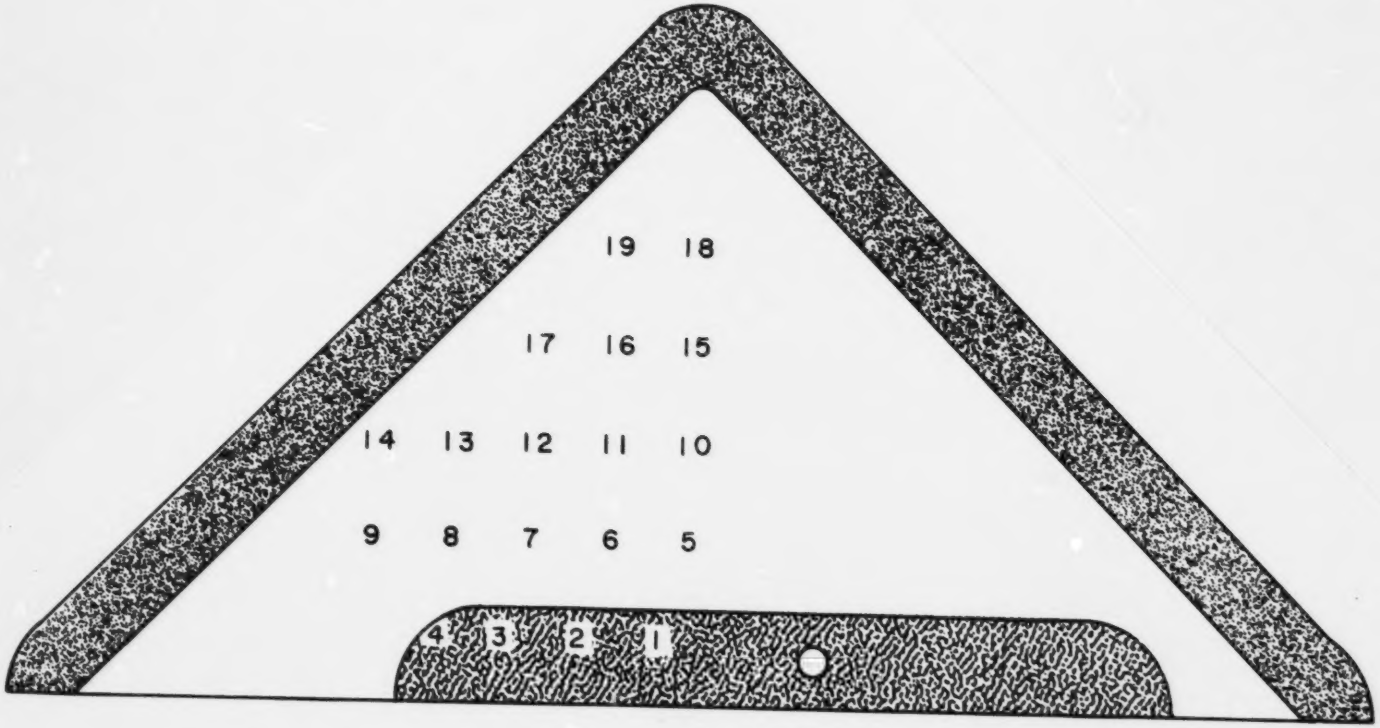

Figure 74. Pile 13, cross-sectional representation: textured area, woodchip cover and base; clear area, sludge-woodchip mixture; circle, perforated flexhose. The numbers indicate the monitoring and control positions: thermocouples, positions 1 through 19; gas sampling probes, adjacent to positions 6 and 16; control thermistor, position 5. The blower was operated in the forced-pressure mode. (The sludge-woodchip mixture was accidentally offset realtive to the woodchip base and this pile, lacking the usual slight longitudinal axis, was nearly symetric.)

set point was 45°C. The experimental plan was to shut down the blower before termination of the period of temperature feedback control, and this was done at hr 176.

The trial period was 27 February 1981 to 18 March 1981. Ambient air temperatures during this period were (°C): mean of the daily highs, 9; mean of the daily lows, zero; mean of the daily means, 4.5; range of the daily highs and lows, -7.8 to 13.9. Precipitation amounted to 7.0 cm in 4 occurrences.

RESULTS

Blower Operation.

Temperature feedback control commenced at hr 48 (Figure 75). Blower operation time increased sharply, until reaching 100% at hr 66. The % time on started decreasing at hr 138, reaching approximately 61% at hr 176. At this time the blower was deliberately shut down.

Temperature.

The temperature record at the innermost series of probes is presented in Figure 76 (all of the temperature data are in Appendix G). Early in the period of temperature feedback control (hr 50 to 65) the temperature ascent at position 5 (site of the control thermistor) paused at approximately the set point value (45°C). The ascent resumed, however, despite 100% blower on time, reaching a peak of 58°C at hr 100. The temperature subsequently declined and, starting at hr 140, stabilized at the set point level. As is characteristic of the Rutgers strategy, a positive temperature gradient in the direction of airflow became established. Deliberate blower shutdown at hr 176 marks the start of a new temperature ascent.

Other temperature records representative of this trial are shown in Figure 77. Probe 1, positioned in the woodchip base adjacent to the flexhose duct, experienced only a slight temperature ascent (10°C to 27°C) prior to blower shutdown, at which point there was a sharp upturn in the temperature (27°C to 70°C). Within the sludge-woodchip mixture the sharpest post-shutdown temperature increase was at position 6 (34°C to 78°C). Two positions near the edge of the pile, 14 and 9, did not increase in temperature subsequent to blower shutdown, but rather decreased.

The temperature data from all of the positions are summarized in TABLE 16 to show the temperature increase resulting from blower shutdown. The mean increase (positions 9 and 14 omitted) was 27.7°C in 20.4 hours (1.36°C/hr).

Gas Analyses.

Prior to shutdown CO_2 was below the limit of detection and O_2 was at the ambient concentration (Figures 78 and 79). Abrupt changes (CO_2 increase and O_2 decrease) coincided with the cessation of mechanical ventilation.

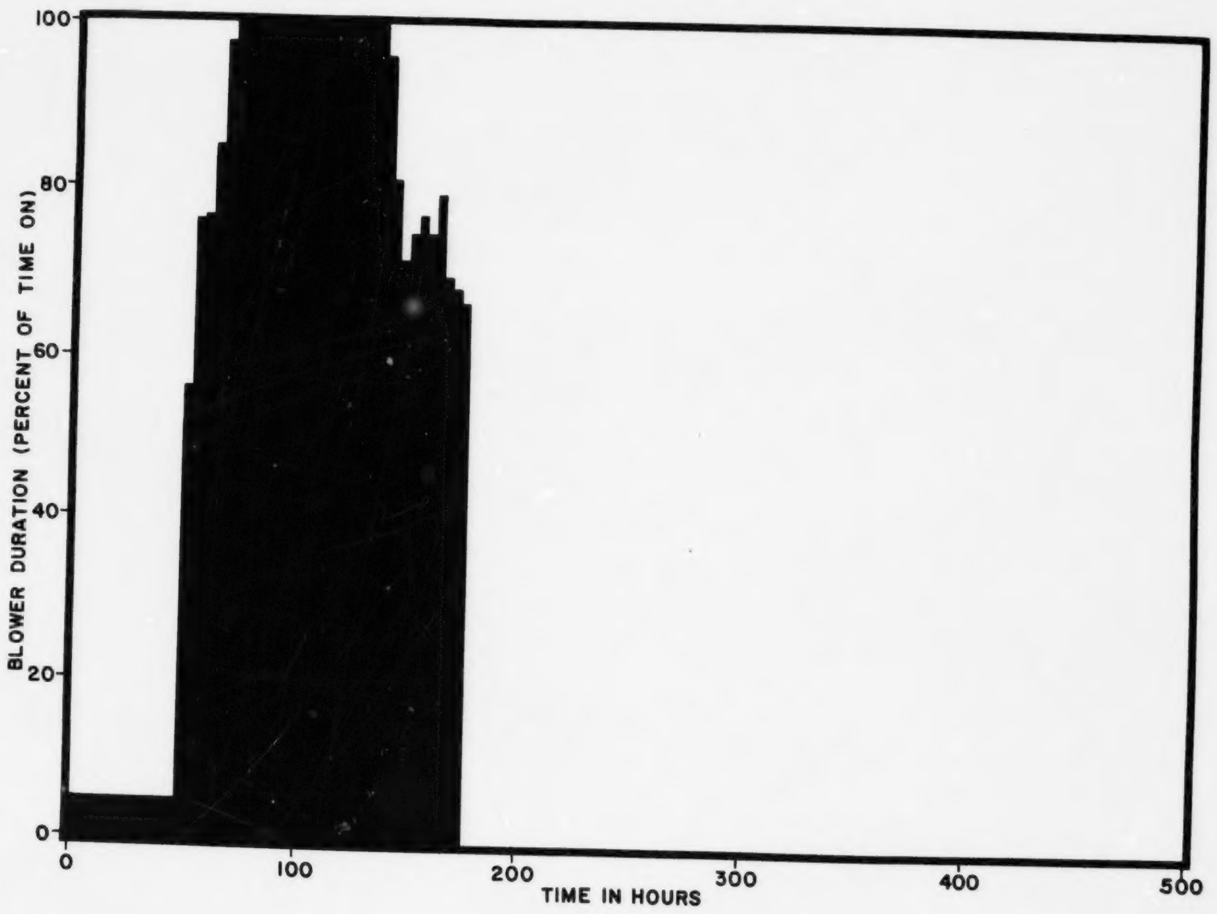

Figure 75. Pile 13, blower operation. The baseline represents operation as scheduled by timer, and the area above the baseline represents blower operation through the temperature-feedback control system. The blower, which was operated in the forced-pressure mode, was shutdown at hr 176.

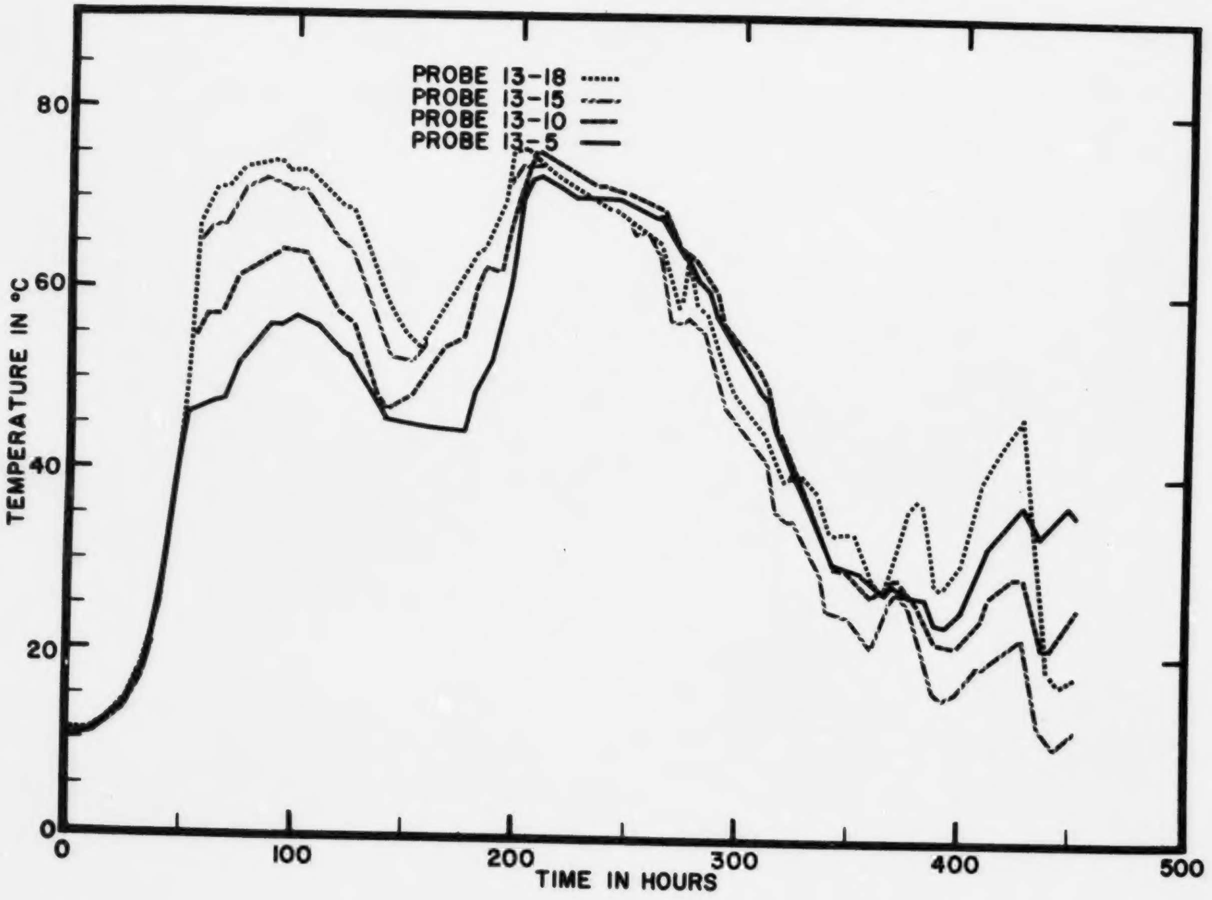

Figure 76. Pile 13, temperature at the innermost vertical series of thermocouples.

Figure 77. Pile 13, temperature at representative positions. Top graph, position 14; middle graph, position 6; bottom graph, position 1.

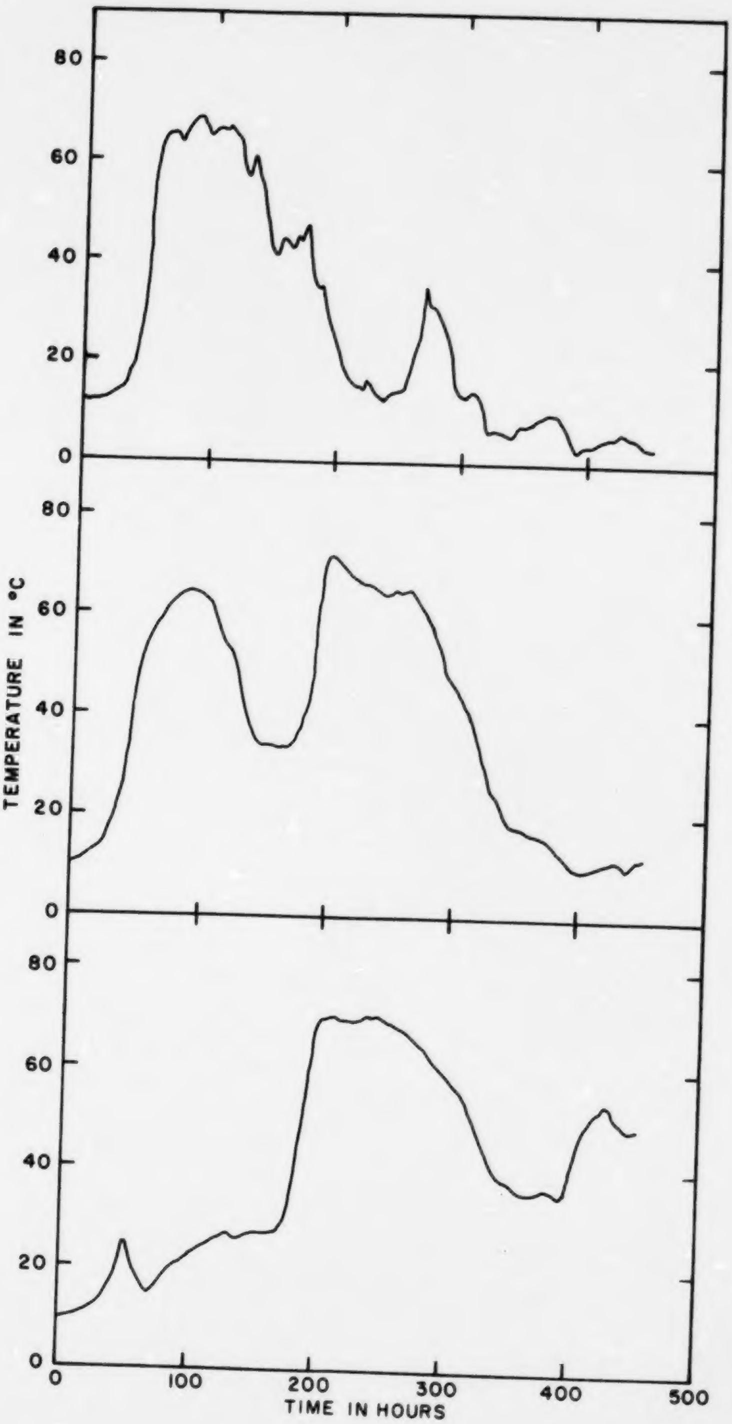

TABLE 16. PILE 13: TEMPERATURE PEAKS RESULTING FROM SHUTDOWN OF THE BLOWER AT HR 176

Thermo-couple*	Pre-shutdown peak		Temp (°C) just prior to shutdown	Post-shutdown peak		Differential (°C)**
	Temp (°C)	Time (hr)		Temp (°C)	Time (hr)	
1	27	175	27	71	240	44
2	36	110	18	67	204	49
3	57	128	27	66	200	39
4	53	100	31	58	186	27
5	57	100	45	75	206	30
6	65	90	34	72	200	38
7	65	100	37	66	190	29
8	63	100	42	60	185	18
9	67	90	49	-†	-	-
10	64	92	54	76	208	22
11	72	85	44	75	194	31
12	73	85	40	73	192	33
13	72	88	47	65	189	18
14	68	88	47	-†	-	-
15	72	85	61	74	200	13
16	73	85	50	76	194	26
17	78	85	48	67	194	19
18	73	90	62	76	200	14
19	74	85	49	71	197	22

* Thermocouples 1 through 4 were positioned in the woodchip base; the other thermocouples were in the sludge-woodchip mixture (see Figure 75).

** Post-shutdown peak temperature minus temperature just prior to shutdown.

† The temperature decreased after blower shutdown.

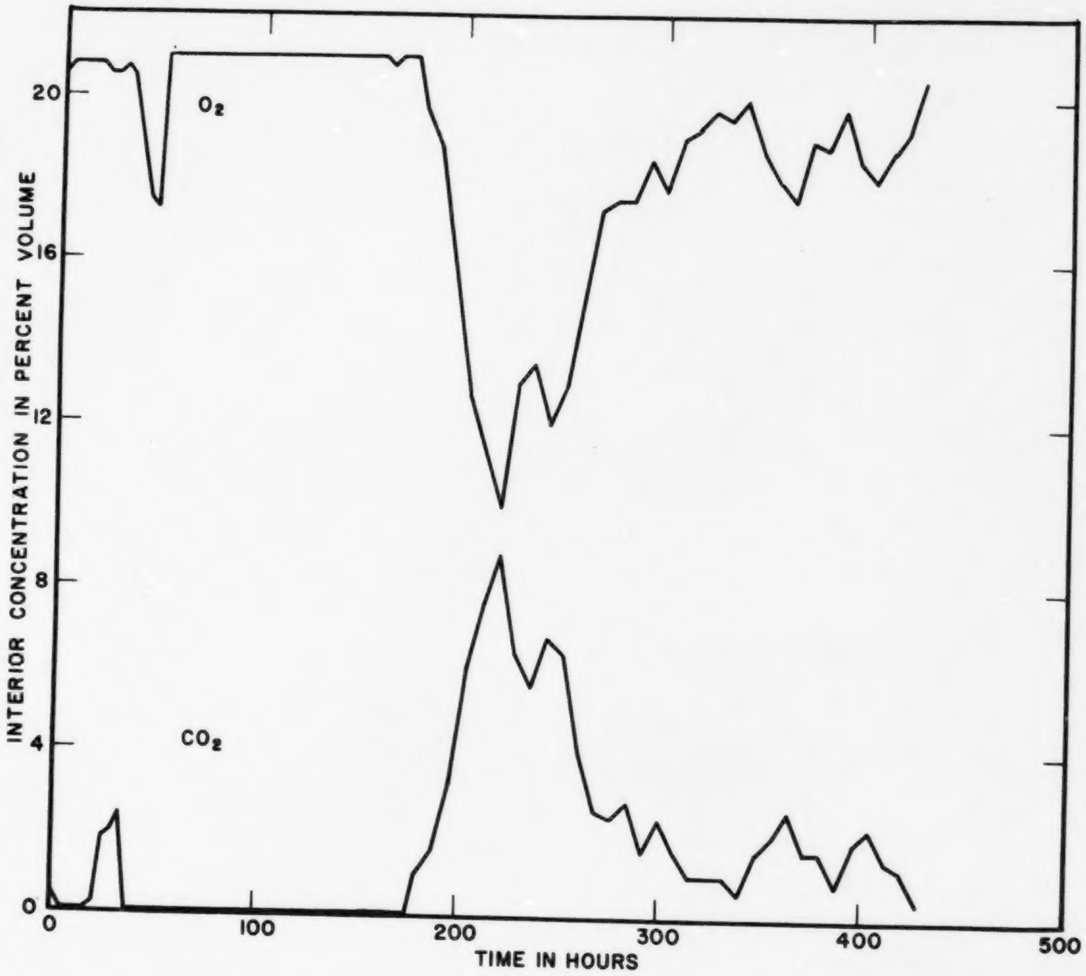

Figure 78. Pile 13, concentrations of 0_2 (upper curve) and $C0_2$ (lower curve). The gas sampling probe was adjacent to position 6.

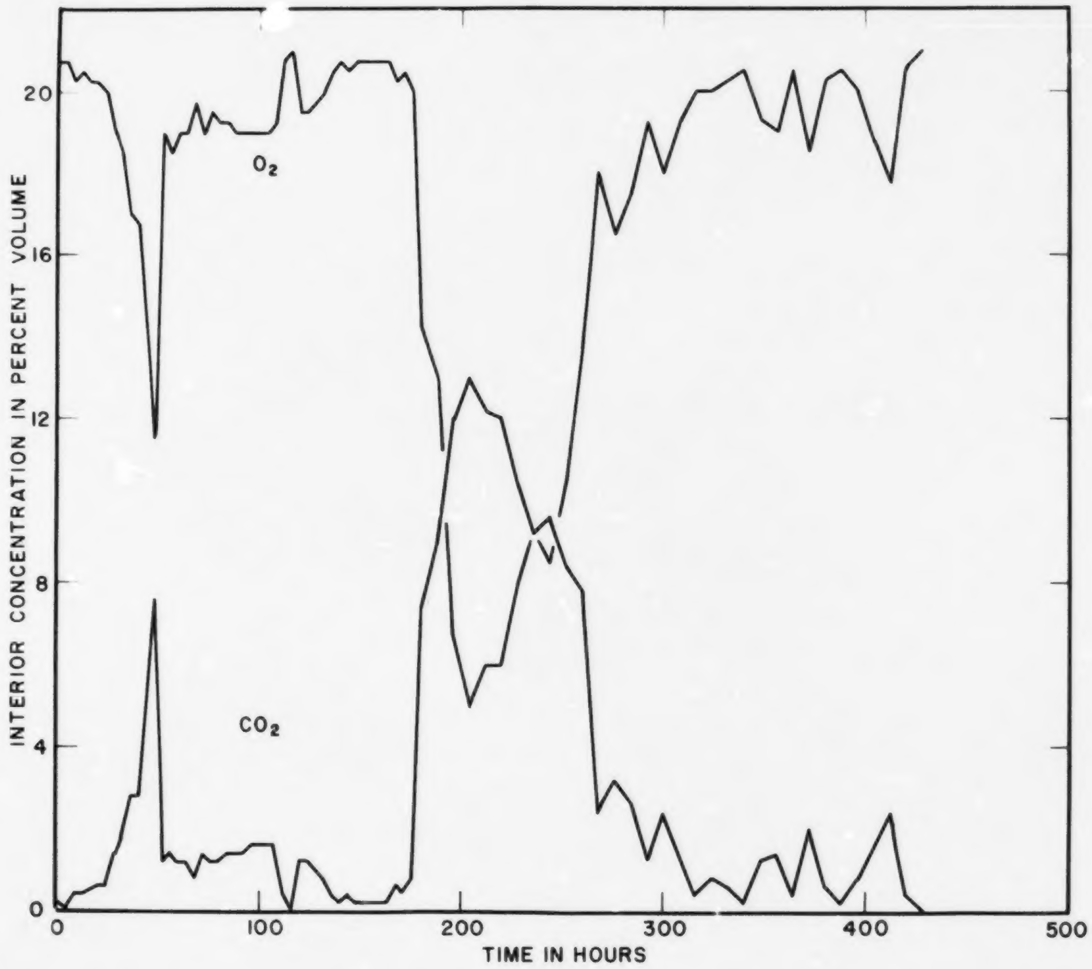

Figure 79. Pile 13, concentrations of O_2 (upper curve) and CO_2 (lower curve). The gas sampling probe was adjacent to position 16.

Moisture Content.

During the first 176 hrs the moisture content decreased from 60% to 43% (Figure 80). In the post-shutdown period a further decrease to 27% occurred.

DISCUSSION

During the period of comparability (up to hr 176) the temperature control achieved in this pile was less precise than in the previous Rutgers piles. This is attributed to the accidental off-center position of the sludge-woodchip mixture relative to the flexhose (Figure 74), presumably leading to uneven air distribution. Thus two factors were non-ideal with respect to the stabilization-water removal objectives: the non-deliberate offset position of the composting pile relative to the flexhose, and the deliberate early shutdown of the blower (hr 176). Despite these factors process performance was satisfactory, judging from the moisture content decrease and informal observations of the odor and visual appearance of the material. Questions of pathogen inactivation aside, the satisfactory performance of pile 13 is indicative of the reliability of the Rutgers strategy, given indifferent routine field practice.

As intended, deliberate blower shutdown induced a sharp temperature upturn. The exceptions (sites 9 and 14) were near the pile's outer edge. The ambient temperature during this trial (mean, 4.5°C) was the coldest of the entire investigation.

These temperature data were analyzed with respect to the federal interim final criteria for pathogen reduction in static-pile composting (48). Three time periods are considered separately (TABLE 17). During the first period the temperatures at positions 1 through 4 (the woodchip base) and position 6 did not meet either of the criteria. The other positions met either the criterion for significant pathogen reduction (spr) or the criterion for further pathogen reduction (fpr). During the post-shutdown period positions 7, 8, 9, 13, 14, and 17 did not meet either of the criteria. Considering the entire trial period, only position 4 (in the woodchip bed) did not meet the criterion for further pathogen reduction, and this position met the criterion for significant reduction. Thus, the induction of harsh temperatures through deliberate blower shutdown improved performance with respect to the federal interim criteria for pathogen inactivation.

The other Rutgers piles (7, 8, 9A, 11A, 11B, 11C) were not deliberately subjected to harsh terminal temperatures and did not perform as well with respect to the federal criteria (TABLE 18). Overall, 76% of the monitoring positions in these piles met the significant reduction criterion, and 41% met the further reduction criterion. The Beltsville pile (9B) met the criterion for further pathogen reduction at all of the monitoring positions. Pile 6A met the criterion for further pathogen reduction at 12 of the 13 sites (see footnote - TABLE 17).

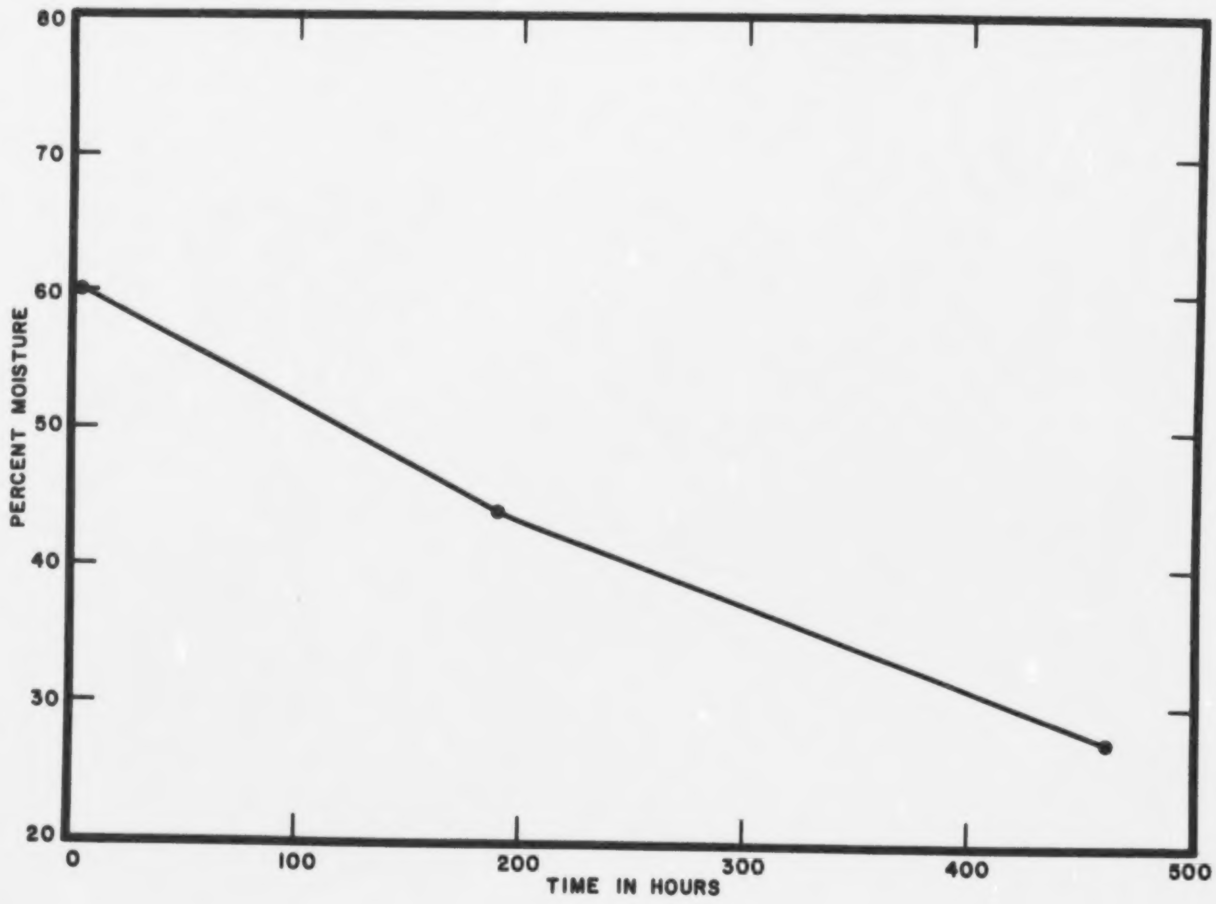

Figure 80. Pile 13, moisture content. Samples taken from central interior locations.

TABLE 17. PILE 13: TEMPERATURE DATA IN TERMS OF THE FEDERAL INTERIM FINAL CRITERIA

Thermo-couple	Pre-shutdown (hr zero to hr 176)			Post-shutdown (hr 176 to hr 445)			Entire trial period (hr zero to hr 445)		
	Hrs $\geq 40^{o}$C	Hrs $\geq 55^{o}$C	Criter-ion met*	Hrs $\geq 40^{o}$C	Hrs $\geq 55^{o}$C	Criter-ion met*	Hrs $\geq 40^{o}$C	Hrs $\geq 55^{o}$C	Criter-ion met*
1	None	None	None	155	120	Fpr	155	120	Fpr
2	None	None	None	128	95	Fpr	128	95	Fpr
3	75	14	None	122	100	Fpr	197	114	Fpr
4	70	None	None	112	5	Spr	182	5	Spr
5	130	28	Spr	230	102	Fpr	360	130	Fpr
6	92	55	None	130	98	Fpr	222	153	Fpr
7	124	72	Fpr	114	40	None	238	112	Fpr
8	132	66	Spr	31	6	None	163	72	Fpr
9	126	81	Fpr	12	None	None	138	81	Fpr
10	130	74	Fpr	280	121	Fpr	410	175	Fpr
11	130	82	Fpr	236	105	Fpr	366	187	Fpr
12	128	88	Fpr	122	42	Spr	250	130	Fpr
13	128	92	Fpr	86	20	None	214	112	Fpr
14	136	88	Fpr	6	None	None	142	88	Fpr
15	264	190	Fpr	132	90	Fpr	396	280	Fpr
16	132	90	Fpr	236	104	Fpr	368	194	Fpr
17	128	97	Fpr	118	38	None	246	135	Fpr
18	118	98	Fpr	270	130	Fpr	388	228	Fpr
19	125	98	Fpr	250	90	Fpr	215	188	Fpr

* Spr = significant pathogen reduction (120 consecutive hrs $\geq 40^{o}$C, plus 4 hrs within the consecutive period $\geq 55^{o}$C).

Fpr = further pathogen reduction (72 consecutive hrs $\geq 55^{o}$C).

TABLE 18. ALL PILES: SUMMARY OF THE TEMPERATURE RECORDS WITH RESPECT TO THE FEDERAL INTERIM FINAL CRITERIA

Pile (report Section)	Control strategy	Mean ambient temp (°C)	Terminal temp elevation	Temp monitoring sites Total (no.)	Meeting indicated criterion (no.) Spr	Fpr	Performance with respect to stabilization and water removal
7(3)	Rutgers	15	No	15	12	6	Good
8(3)	Rutgers	21	No	31	20	6	Good
9A (3)	Rutgers	27	No	19	17	13	Good
4A (4)	Rutgers	14.5	No	12	11	2	Good
11A (5)	Rutgers	9	No	12	11	6	Good
11B (5)	Rutgers	9	No	12	8	6	Good
11C (5)	Rutgers	9	No	12	7	7	Good
13 (11)	Rutgers	4.5	Yes*	19	19	18	Good
9B (3)	Beltsville	27	N/A	15	15	15	Poor
6A (10)	N/A†	11	N/A	13	12‡	12‡	Failed

* Terminal harsh temperatures induced (present Section)

† The intention was to manage this pile according to the Rutgers process, but the processing failed because of inadequate air penetration (see Section 10).

‡ One position (position 5 - see Figure 74) did not literally meet either criterion, but it experienced the following temperatures: peak, 71°C; 49 consecutive hrs at $\geq$ 55°C; 116 hrs (in three intervals) at $\geq$ 40°C.

In contrast, with respect to the stabilization-water removal objective the Rutgers piles performed well, the Beltsville pile performed poorly, and pile 6A failed.

These observations should be put into perspective. Except for the present Section, this investigation concerns the stabilization-water removal objective. As such, the thermocouples were not positioned specifically for the purpose of determining compliance with the Federal criteria. For example, pile 9B (Beltsville process) lacked a series of thermocouples next to the interface with the woodchip cover (compare Figures 17 and 18). The material in this region is suspect because of its proximity to the pile's edge, and because the vacuum-induced direction of ventilation would further promote coolness. Another deficiency, from the viewpoint of monitoring for compliance with the Federal criteria, is the lack of probes in the pile "toes." This refers to the part of the pile forming a triangle with the woodchip base or the concrete pad. Because of the direction of ventilation, the "toes" of Beltsville piles are particularly subject to coolness. These considerations illustrate the obvious point that the reliability of "compliance data" is strongly dependent on the frequency of monitoring and the selection of positions for the monitoring.

The problem of monitoring may be less intractable in routine practice than might appear from a consideration of these freestanding piles. This is because the extended pile geometry would presumably be used for the Rutgers strategy in static pile configuration, as it is in routine Beltsville-type operation. The ratio of exposed edges to interior volume is less with such geometry.

Despite the accumulation of considerable routine operational experience with the Beltsville process, published systematic studies of the capability of this process to comply with the Federal interim final criteria seem to be lacking. Furthermore, other than pile 9B, we know of no published report on the Beltsville process which provides sufficiently detailed data to support an interpretation of the time-temperature observations in reference to the criteria.

An independent side-by-side comparison of the Rutgers and Beltsville approaches, involving a mixture of refuse and sewage sludge, included tests for Salmonella as one of the many points of comparison (34). All of the tests relating to stabilization, including changes in moisture content, indicated that the Rutgers strategy gave superior performance. With respect to the decrease in Salmonella both processes performed comparably.

TABLE 19 summarizes our thoughts regarding the relative merits of the Rutgers and Beltsville approaches with respect to the pathogen inactivation objective. Some of the points are necessarily speculative. The present state of knowledge does not indicate that one, or the other, of these approaches is superior with respect to sanitation. Both are highly effective in this respect.

TABLE 19. RELATIVE MERITS OF THE RUTGERS HIGH RATE STAGE AND THE BELTSVILLE "ACTIVE STAGE" WITH RESPECT TO SANITATION.

Point of comparison	Comments
Harsh temperatures (e.g. 75°C-80°C)	Intrinsic to the Beltsville process; inducible as a terminal step of the Rutgers strategy.
Biological antagonisms	Presumably more effective in the Rutgers strategy.
Cool spots	"Toes": Beltsville more subject to problem. Outer edges: Beltsville more subject to problem. Interior (near flexhose): Rutgers more subject to problem (but not if terminal harsh temperatures induced).
Dryness as a sanitizing agent	Operative only in the Rutgers strategy.
Observed *Salmonella* reduction	Rutgers and Beltsville approaches performed comparably (34).
Potential for regrowth of *Salmonella*	Less potential in Rutgers strategy, as substrate is more thoroughly decomposed.

Finally, the potential role of the curing stage in assuring product safety should be considered. The advantages of emphasizing the curing stage to insure sanitation, relative to the high rate stage, are as follows. 1) The curing stage is closer, with respect to time, to the point of end-product usage. This decreases the opportunity for post-processing recontamination or regrowth. 2) Large well-insulated curing piles presumably will gradually self-heat to harsh temperatures, even though formed of material thoroughly stabilized and dried in the high-rate stage. 3) Large piles have a relatively low surface to volume ratio. This minimizes the volume of "edge material" exposed to ambient conditions. 4) It seems probable from item 3) that, in routine practice, monitoring of the curing stage would provide the more reliable time-temperature data to insure pathogen inactivation.

Composting is an excellent means of sanitizing waste. Regardless, we believe that the high-rate stage should be managed primarily to accomplish stabilization and water removal objectives. If the intended use of the end-product requires additional assurance of pathogen reduction this can be achieved through a terminal harsh temperature phase of processing, or through a curing strategy designed with product safety assurance as one of its objectives.

SECTION 12

UNIFORM PROVISION OF AIR ALONG THE LENGTH OF A COMPOSTING PILE[*]

INTRODUCTION

If the composting pile is relatively long, and the area of air holes is uniform along the length of the duct, delivery of air to the pile is non-uniform. This is because more air exits from the part of the duct close to the blower than from the distant part. With the control thermistor placed midway between the ends of the pile, the part of the pile close to the blower is overventilated (too cool) and the more distant part underventilated (too hot).

A means of providing air uniformly in the longitudinal dimension is to vary the size and/or spacing of the air holes along the length of the duct, such that the amount of air vented is similar regardless of distance from the blower. A computer program, presented herein, was developed to help the user determine the number of evenly spaced holes, of a given hole size, necessary to supply a given amount of air to a 5 foot[†] section of duct. Each succeeding 5 foot section is treated separately. A spacing scheme for one to 20 holes per section is stored in the program. Depending on the length of the pile, it may be advantageous to increase the size of the holes in progressive sections of the duct.

CALCULATION[‡]

The airflow out of each hole in the duct is calculated through the use of two equations (52). The first involves the pressure drop in the duct, as follows:

$$\Delta P = \frac{0.81 f L \rho q^2}{D^5} \qquad \text{(i)}$$

where: f = the Moody friction factor (dimensionless)

L = the length of duct (ft)

ρ = fluid density (slugs/ft^3)

q = flow (ft/sec)

D = duct diameter (ft).

Comments on these factors are as follows:

---

[*] An early, flawed, version of this Section was published (51). A correction was submitted to the publisher.

[†] To change feet to meters, multiply by 0.305.

[‡] We thank the following individuals for kindly reviewing the calculations: James H. Miller, Roberto C. Leon, Dr. Robert C. Ahlert.

Moody friction factor (f). Tables of values of this factor are found in fluid dynamics textbooks. Also, the Fanning friction factor may be used (Fanning factor = Moody factor/4). For the present application (commercial pipe serving as duct, high velocity) the Moody friction factor is roughly 0.02.

Length of duct (L). This refers to the total length of duct, including parallel lengths where used.

Fluid density (ρ). The value used in the program is $\rho = 0.00238$ slugs/ft^3.*

Velocity (V). This is the mean cross-sectional velocity.

Diameter (D). The user selects the duct diameter.

The second equation is used to calculate the airflow out of each hole, as follows:

$$q_e = 0.0071 d^2 \sqrt{\frac{(P_{duct} - P_{exit})}{\rho K}} \qquad \text{(ii)}$$

where: q_e = the exit flow (ft/^{3}sec)

P_{duct} = the pressure in the duct at that point (lb/ft^2)†

d = hole diameter (in.)

P_{exit} = the pressure in the pile

K = constant

Comments on these factors are as follows:

Pressure in the pile. Since instantaneous pressure should not vary along the length of the pile, it is set equal to zero.

Constant. In this program K is set equal to 1.5.

COMPUTER PROGRAM - BACKGROUND

List of things that the user must know to enter the program

Pressure at entrance to duct (lb/ft^2). The pressure at the entrance to the first section of duct must be known. The pressure at this point is the pressure at the blower (e.g., as specified by the manufacturer) minus the pressure drop over the distance to the first section. The user should also subtract the pressure loss from the ductwork to the outer edge of the pile (the pile backpressure). If this is not known, a conservative estimate is 1.0 lb/ft^2. The pressure at the exit of the first section is the entrance pressure at the second section, etc. The pressure at the blower must provide adequate pressure to the terminal section of duct. This is satisfied when the number of holes required in the terminal section is <20, and the required hole diameter is reasonably less than the duct (pipe) I.D.. The use of a blower delivering higher pressure than necessary yields a solution involving fewer holes and/or smaller holes, but this represents an uneconomical approach. A suggested first approximation for pressure at the blower is 6.0 lb/ft^2.

---

*To change slugs/ft^3 to kg/m^3, multiply by 3.99×10^{-4}.

†To change lb/ft^2 to kgm/m^2, multiply by 4.873.

Flow at entrance to duct (cfs)*. The estimation of the required air flow from the holes into the pile is based on pile 9A (Section 3) as this is the largest pile in our experience (40 ton),† and as it yields the largest (hence the most conservative) estimate. Furthermore, the estimate is conservative for use with other sludges, as the experimental material was primary sludge with a high volatile solids content (∿ 75%). This pile was ventilated by six 1/3 hp blowers at each end of the pile. The blowers were operated in unison. Each blower discharged into a 20 foot length of perforated duct, which was capped at the distal end. Since the total length of perforated duct was 120 feet, for calculation purposes there are twenty-four 5 foot lengths.

The peak demand exerted was 71.3 cfm per wet ton‡ (initial weight), which is rounded off to 80 cfm per ton for purposes of the estimation. Since the pile weighed approximately 40 tons, the total peak demand was 3200 cfm§. The total length of pipe was 120 feet, arranged in three parallel branches of equal length. Thus there were twenty-four 5 foot sections, with each section requiring 133.3 cfm. For use in the program this is converted to cfs (2.22 cfs).

Duct pipe diameter (ft). The use of standard pipe ID's is recommended.

Friction factor. This depends on duct size, material, and airflow, as described above.

Hole diameter, in 32nds of an inch. Different values should be entered in different runs of the program to find the best combination of number and size of holes for each 5 foot section of duct. An input of 99 will end the program.

---

*To change from cfs to m^3/sec, multiply by 2.83×10^{-2}.

†To change ton to tonne, multiply by 1.1023.

‡To change from cfm/ton to m^3/sec-tonne (metric), multiply by 4.232×10^{-4}.

§To change from cfm to m^3/sec, multiply by 4.720×10^{-4}.

Output

XXXX/32 inch*	XX holes	XXX.XXCFS	XXX.XXPSF
The hole size (inputted)	The number of holes selected by computer	Exit flow from the holes	Pressure at the end of the section

Two output values are provided each time the program is run. The first is the value for the number of holes giving slightly less than the desired exit flow. The second is the value for the number of holes giving slightly greater than the desired exit flow.

Notes

a. The first step in putting the program on line is to establish the file on hole spacing. This is provided in TABLE 20 (the "H.DAT" file).

b. All of the values inputted to run the program must be real numbers, rather than integers. Always include a decimal point.

List of Variables

AL (20,21)	Array storing distance between each hole for 1-20 holes. Does not change through the program.
PREF	Duct pressure in PSF. Changes in line 290, 330 and 240.
PREM	Duct pressure in PSF. Does not change. Used for program to remember initial pressure.
CFS	Flow in pipe (CFS). Changes in lines 270 and 310.
CFSM	Flow in pipe (CFS). Does not change (used like PREM)
FF	Friction factor. Does not change.
DUCT	Duct diameter in feet. Does not change.
EXF	Exit flow from holes in CFS. Does not change.
I (First use)	Counter for filling "AL" array (Line 150).
J	Counter for filling "AL" array (Line 150) and line 320.
DIA	Exit hole diameter (32nd's of an inch). Changes in line 180.
N	Counter used in pulling data from "AL". (Depicts number of holes.) Changes in lines 200 and 220.
FL	Exit flow from holes (CFS). Changes in lines 250 and 300.
FS	Exit flow from holes (CFS). Acts to remember most recent value of "FL". Changes in line 230.

---

* to change from inches to cm, multiply by 2.54.

TABLE 20. "H. DAT" (HOLE DATA) FILE

```
0. 5. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 2.5 2.5 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 1.667 1.667 1.667 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 1.25 1.25 1.25 1.25 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 1. 1. 1. 1. 1. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0. 1.667 0. 1.667 0. 1.667 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
0. .7083 .7083 .7083 .7083 .7083 .7083 .7502 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0. 1.25 0. 1.25 0. 1.25 0. 1.25 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
0. .5521 .5521 .5521 .5521 .5521 .5521 .5521 .5521 .5832 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.
0. 0. 1. 0. 1. 0. 1. 0. 1. 0. 1. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
0. .4583 .4583 .4583 .4583 .4583 .4583 .4583 .4583 .4583 .4583 .4170 0. 0. 0. 0. 0. 0.
  0. 0. 0.
0. 0. .8333 0. .8333 0. .8333 0. .8333 0. .8333 0. .8335 0. 0. 0. 0. 0. 0. 0. 0.
0. .3854 .3854 .3854 .3854 .3854 .3854 .3854 .3854 .3854 .3854 .3854 .3854 .3752 0. 0.
  0. 0. 0. 0. 0.
0. 0. .7083 0. .7083 0. .7083 0. .7083 0. .7083 0. .7083 0. .7502 0. 0. 0. 0. 0. 0.
0. .3333 .3333 .3333 .3333 .3333 .3333 .3333 .3333 .3333 .3333 .3333 .3333 .3333 .3333
  .3338 0. 0. 0. 0. 0.
0. 0. .625 0. .625 0. .625 0. .625 0. .625 0. .625 0. .625 0. .625 0. 0. 0. 0.
0. .2917 .2917 .2917 .2917 .2917 .2917 .2917 .2917 .2917 .2917 .2917 .2917 .2917 .2917
  .2917 .2917 .3328 0. 0. 0.
0. 0. .5521 0. .5521 0. .5521 0. .5521 0. .5521 0. .5521 0. .5521 0. .5521 0. .5832 0.
  0.
0. .2604 .2604 .2604 .2604 .2604 .2604 .2604 .2604 .2604 .2604 .2604 .2604 .2604 .2604
  .2604 .2604 .2604 .2604 .3128 0.
0. 0. .5 0. .5 0. .5 0. .5 0. .5 0. .5 0. .5 0. .5 0. .5 0. .5
0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
```

PRES Duct pressure in PSF. Acts like "FS". Changes in line 240.

I (Second use) Counter to pull data from "AL". Changes in line 280.

NC Simply N-1 used to modify output of line 370. Changes in line 360.

THE PROGRAM

```
@ Type Pipes, for
 10    REAL   AL(20,21)
 20    WRITE(5,440)
 30    READ(5,*)DUCT
 40    WRITE(5,450)
 50    READ(5,*) EXF
 60    WRITE(5,400)
 70    READ(5,*)PREF
 80    PREM=PREF
 90    WRITE(5,410)
100    READ(5,*)CFS
110    CFSM=CFS
120    WRITE(5,420)
130    READ(5,*)FF
140    OPEN (UNIT=29,DEVICE='dsk:',FILE='H.DAT')
150    READ(29,*)    ((AL(I,J),J=1,21),I=1,20)
160    CLOSE(UNIT=29)
170    WRITE(5,430)
180    READ(5,*)DIA
190    IF(DIA.EQ.99.)GO    TO   390
200    N=1
210    GO   TO   250
220    N=N+1
230    FS=FL
240    PRES=PREF
250    FL=O
260    PREF=PREM
270    CFS=CFSM
280    DO   310I=1,N
290    PREF=PREF-(AL(N,I)*(CFS**2)/(DUCT**5)*FF/519)
```

```
300   FL=FL+(0.000126*(DIA**2)*(PREF**0.5))
310   CFS=CFSM-FL
320   J=N+1
330   PREF=PREF-(AL(N,J)*(CFS**2)/(DUCT**5)*FF/519)
340   IF(FL.LT.EXF)GO   TO   220
350   WRITE(5,460)N,DIA,FL,PREF
360   NC=N-1
370   WRITE(5,460)NC,DIA,FS,PRES
380   GO    TO    170
390   STOP
400   FORMAT('     ', 'INPUT   ENTRANCE   PRESSURE   IN   PSF')
410   FORMAT('     ', 'INPUT   ENTRANCE   FLOW   IN   CFS')
420   FORMAT('     ', 'INPUT   FRICTION   FACTOR')
430   FORMAT('     ', 'INPUT   DIA    IN   32NDS   OF   AN
      INCH   OR   99   TO   END')
440   FORMAT('     ', 'INPUT   DUCT    DIAMETER    IN    FEET')
450   FORMAT('     ', 'INPUT   EXIT    FLOW   PER   5   FT
      OF     DUCT    IN     CFS')
460   FORMAT('     ',I2,'  HOLES',F4.0,'/32      IN.',F7.2',
      CFS',F8.2',    PSF')
470   END
```

DISCUSSION

In the developmental phase of the Rutgers strategy non-uniform distribution of air was not a significant problem, as this involved relatively small (pilot scale) piles. Moreover, the largest pile (9A-40 tons) was served by blowers at both ends of the pile, and the longest continuous length of perforeated duct was only 20 feet. Routine operation, however, would involve longer piles, and a facility layout having blowers at only one end is preferred. In the absence of a specific design remedy, this would result in non-uniform ventilation and degraded performance. One such remedy was developed herein.

CONCLUSIONS

- The composting system tends to accumulate metabolically generated heat excessively, leading to inhibitively high temperature. The threshold to significant inhibition is approximately 60°C, and its severity increases sharply at higher temperatures. At 80°C (common peak temperature) the rate of decomposition is extremely low.

- This tendency can be controlled through ventilative heat removal in reference to temperature. The main mechanism of heat removal is evaporative cooling, establishing a drying tendency. Implementation is via temperature feedback control of a blower(s), using standard (non-proprietary) equipment. The forced-pressure mode of ventilation is more efficient than the vacuum-induced mode. In this manner an operational ceiling of 60°C is maintained.

- Blower capacity (head and volume) must suffice to meet peak demand for ventilation, as expressed through feedback control. A strong waste (e.g. raw sewage sludge) demands more ventilation than a weak one (e.g. digested sludge).

- A temperature gradient is established along the axis of airflow, whereas drying is relatively uniform. The temperature gradient imposes a height limitation, above which a high rate of decomposition is not realizable.

- Managed thusly, decomposition and drying are related in that the decomposition generates heat, the heat vaporizes water, and the vaporization causes drying. Hence, the stronger the drying tendency the faster the sludge decomposition.

- A consequence of temperature feedback control is that the composting mass is well-oxygenated, because more air is needed to remove heat than to resupply 0_2.

- This strategy permits the use of recycled compost as the bulking agent, in static pile configuration.

- This strategy, compared to a conventional approach, resulted in 4x more sludge decomposition in half the time

- The cost of ventilation for water removal through composting and non-biological air drying was as follows: composting, $0.32/tonne water removed ($0.31/ton); air drying, $6.43/tonne water removed ($6.33/ton). This difference results from the biological generation of heat at the expense of putrescible organic material in the sludge.

RECOMMENDATIONS

- Maximization of decomposition rate should be the explicit goal of composting process design and control.
- Rate maximization should be approached through temperature feedback control of a blower(s).
- The rate of decomposition should be assessed in terms of the demand for ventilation, and the course of drying.
- This strategy (which focuses on temperature feedback control) should be implemented at lowest possible construction cost, consistent with operational considerations.
- The unenclosed static pile configuration is structurally simple and eminently suitable for implementation, and should be the preferred configuration.

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APPENDIX A-1

Temperature Observations for Piles 7, 8, 9A and 9B

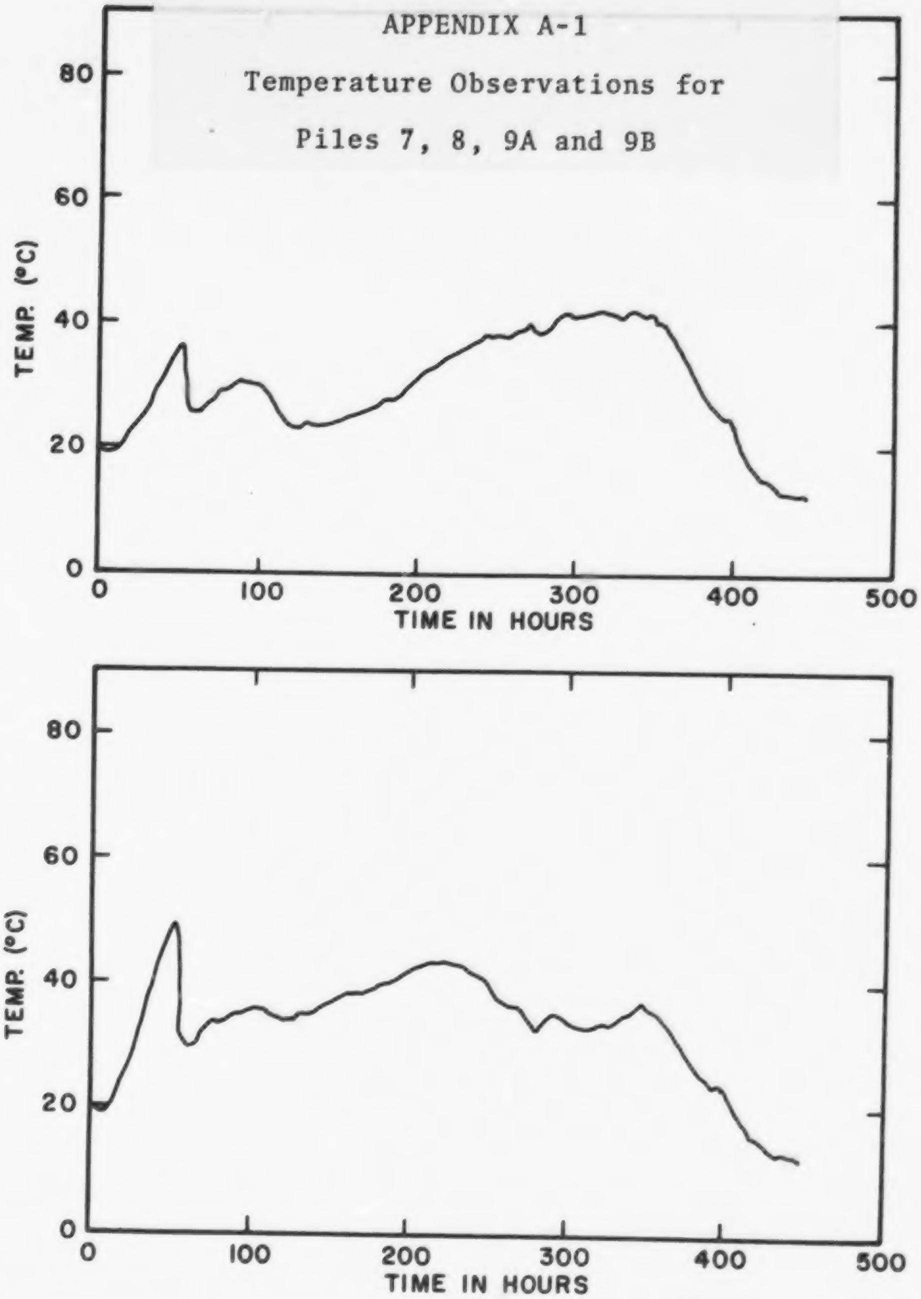


Figure 81. Pile 7, temperature at position 1 (upper plot) and position 2 (lower plot).

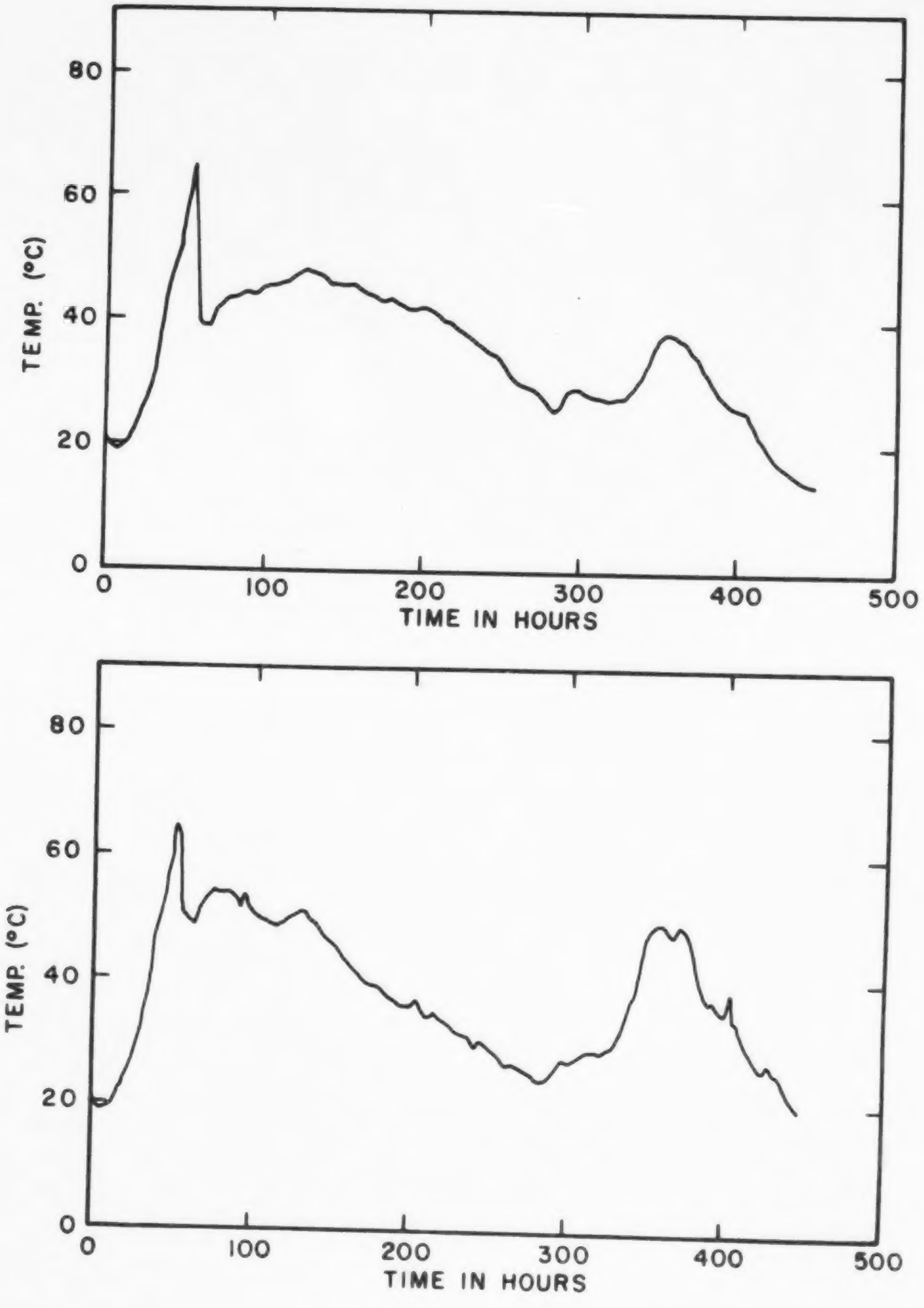


Figure 82. Pile 7, temperature at position 3 (upper plot) and position 4 (lower plot).

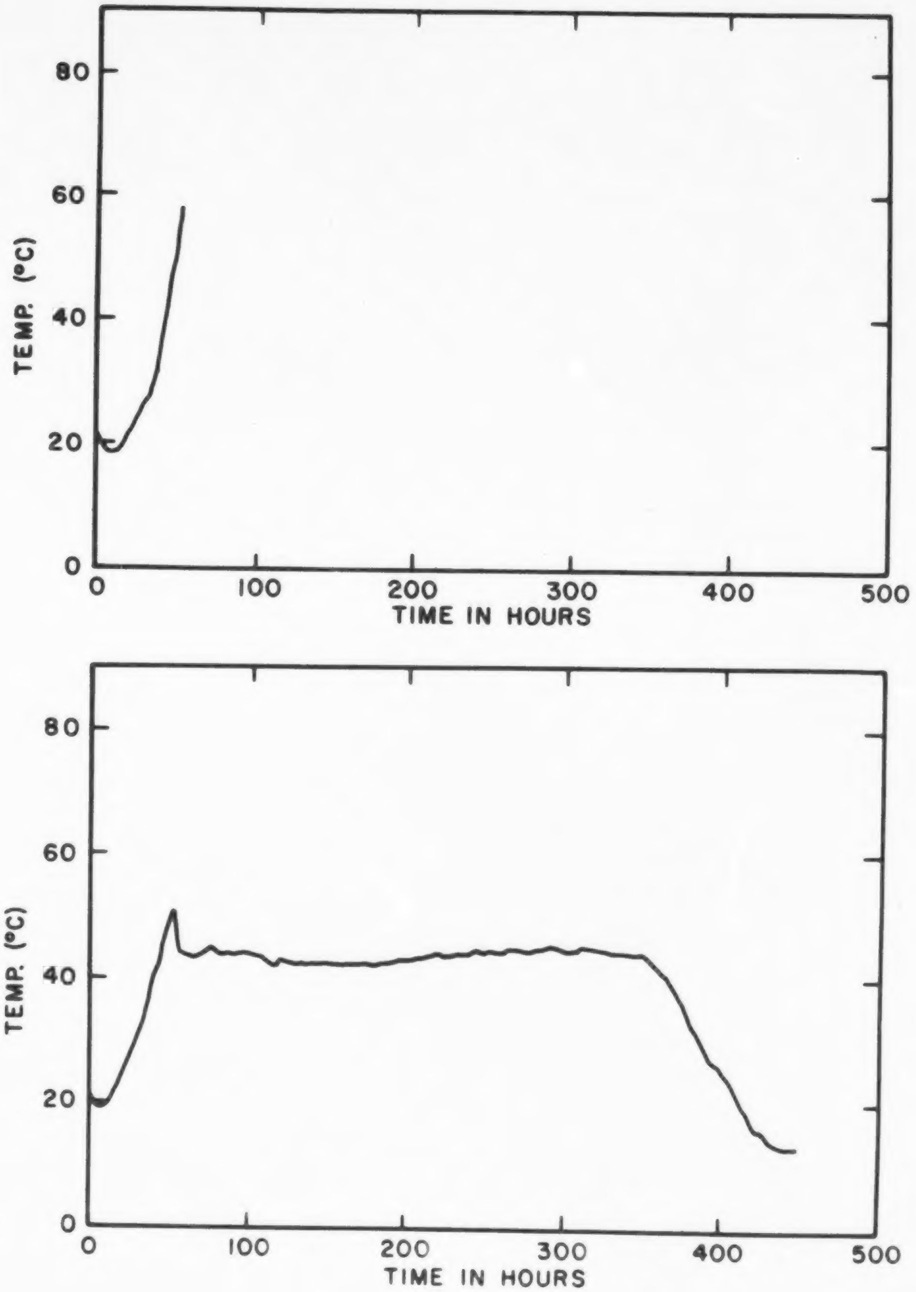


Figure 83. Pile 7, temperature at position 5 (upper plot) and position 6 (lower plot).

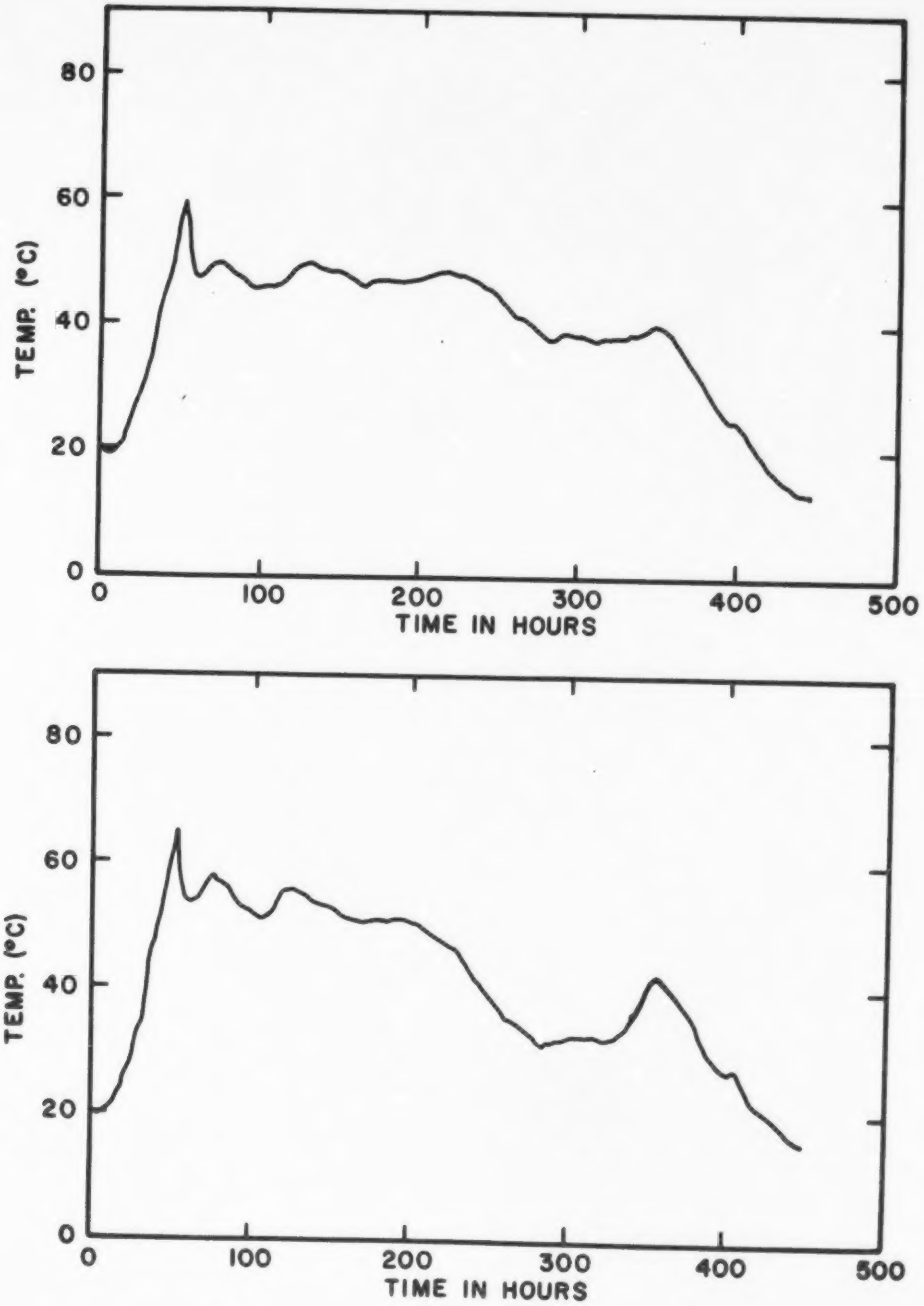


Figure 84. Pile 7, temperature at position 7 (upper plot) and position 8 (lower plot).

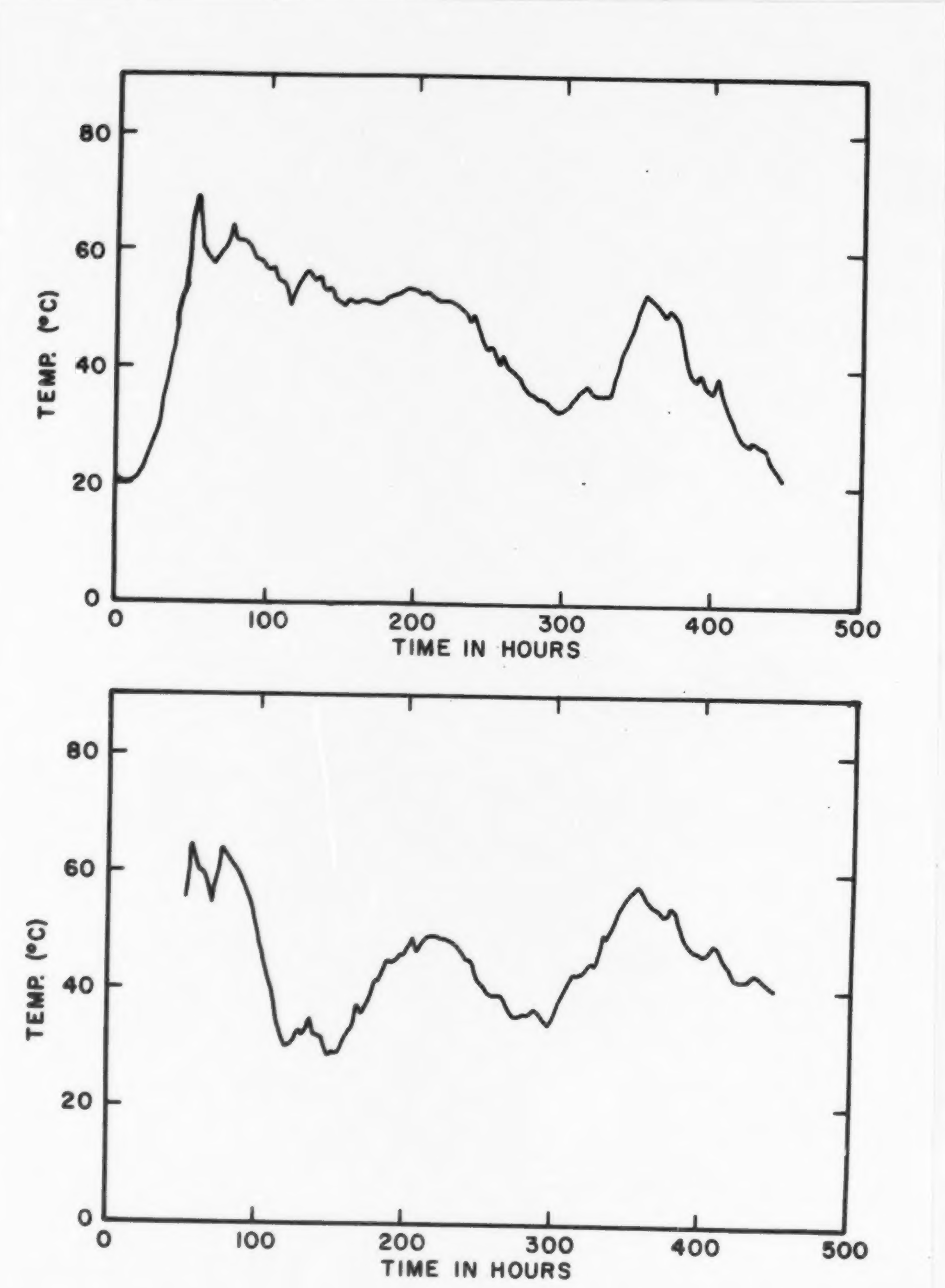


Figure 85. Pile 7, temperature at position 9 (upper plot) and position 10 (lower plot).

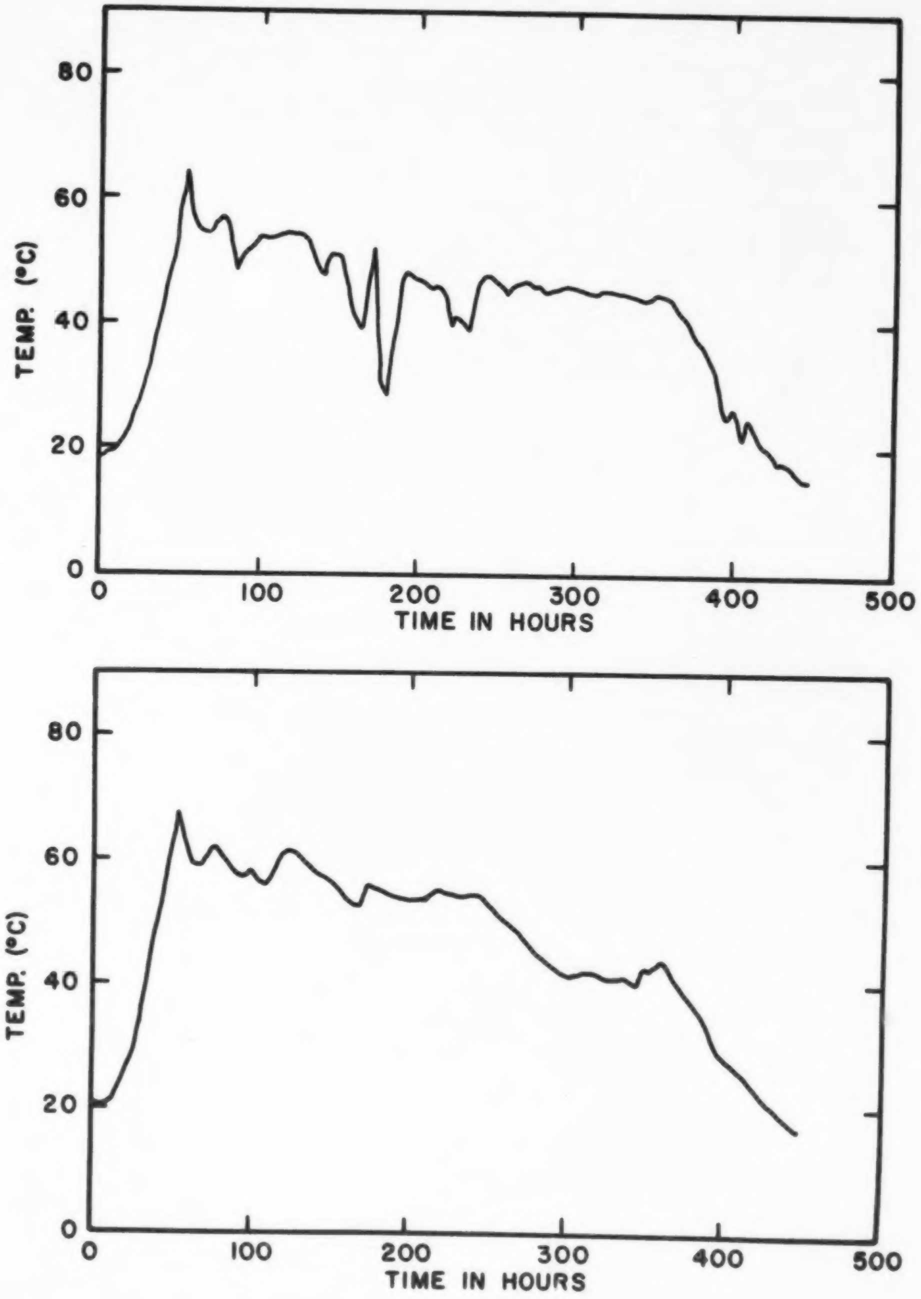


Figure 86. Pile 7, temperature at position 11 (upper plot) and position 12 (lower plot).

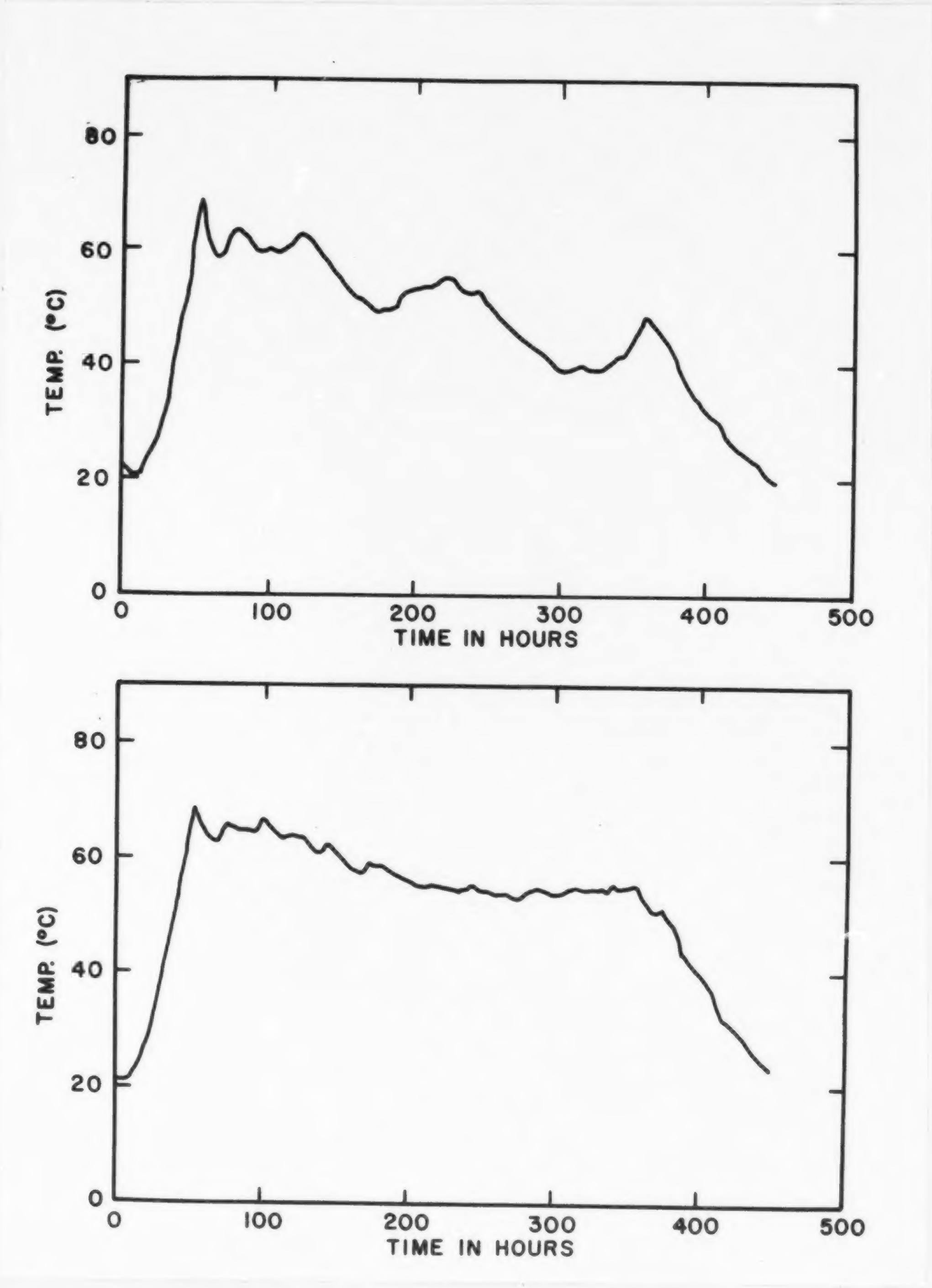


Figure 87. Pile 7, temperature at position 13 (upper plot) and position 14 (lower plot).

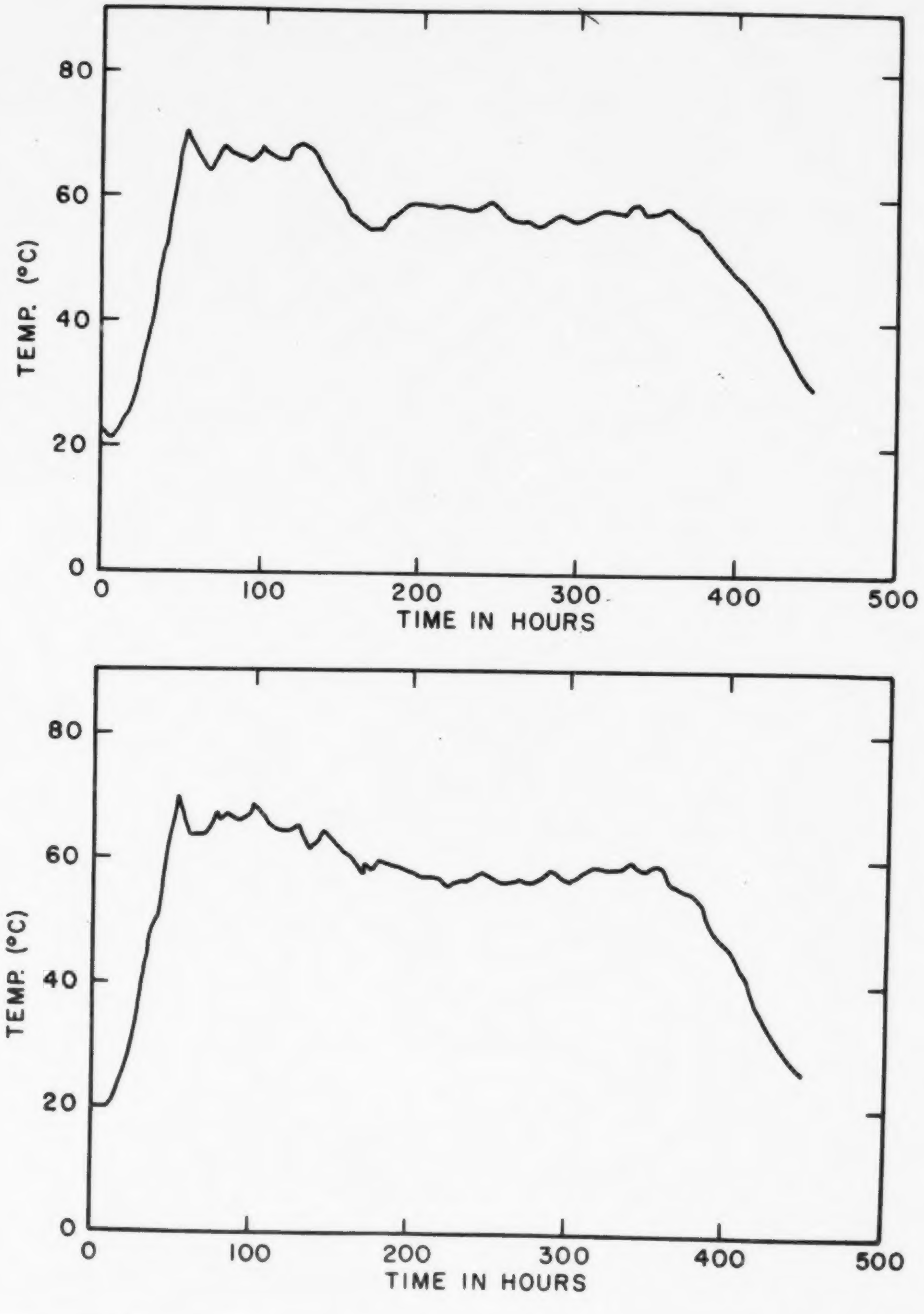


Figure 88. Pile 7, temperature at position 15 (upper plot) and position 16 (lower plot).

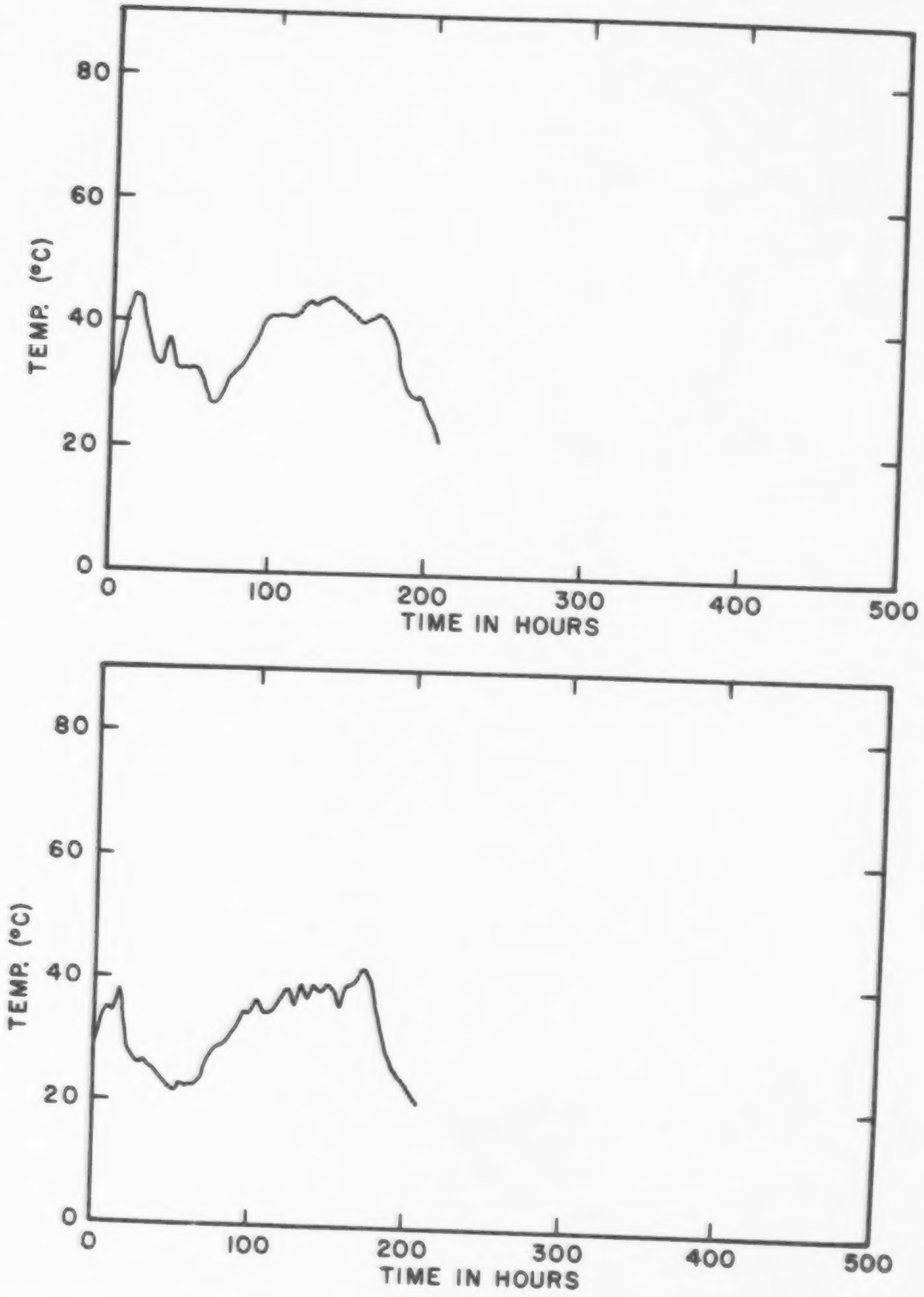


Figure 89. Pile 8, temperature at position 1 (upper plot) and position 2 (lower plot).

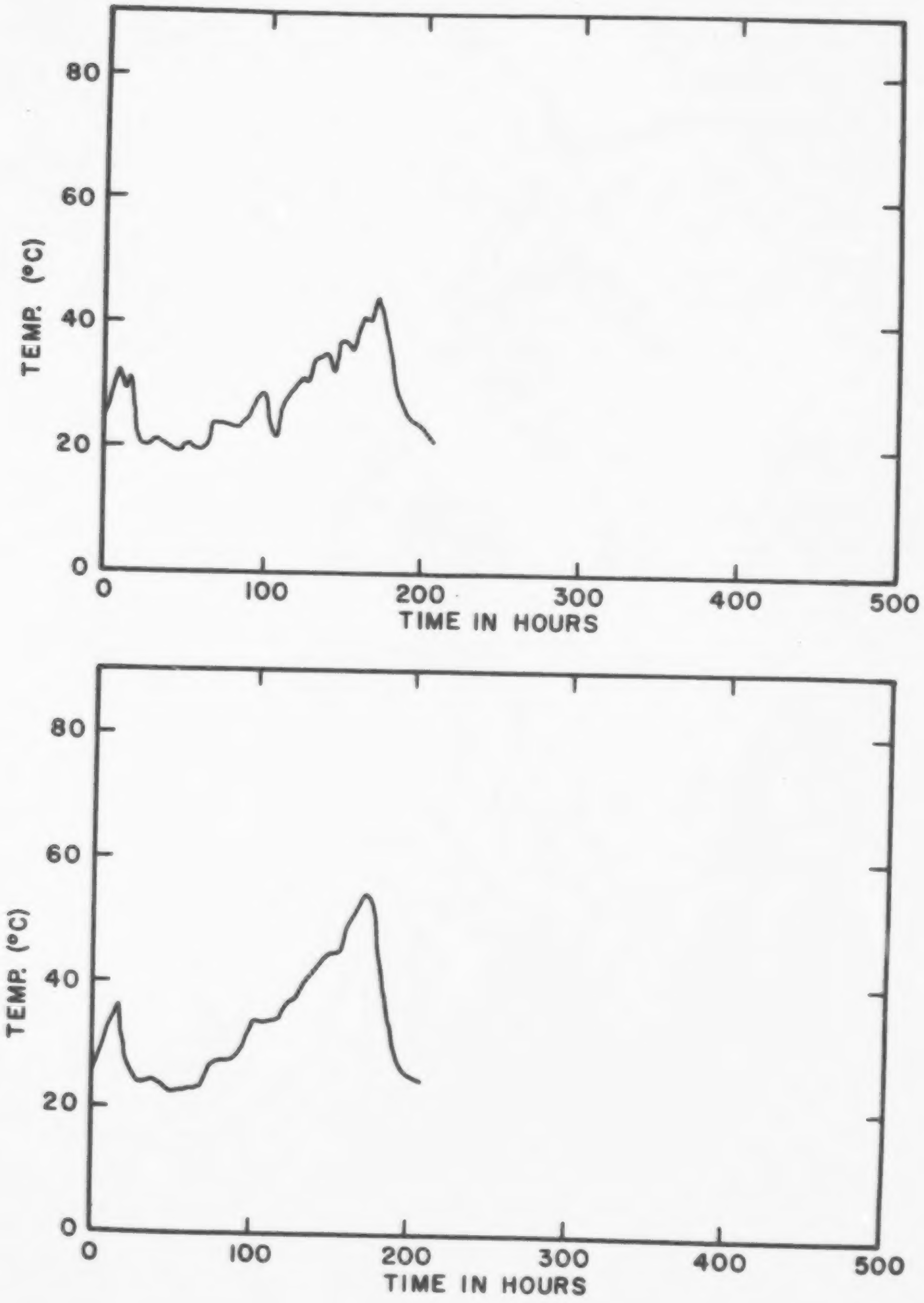


Figure 90. Pile 8, temperature at position 3 (upper plot) and position 4 (lower plot).

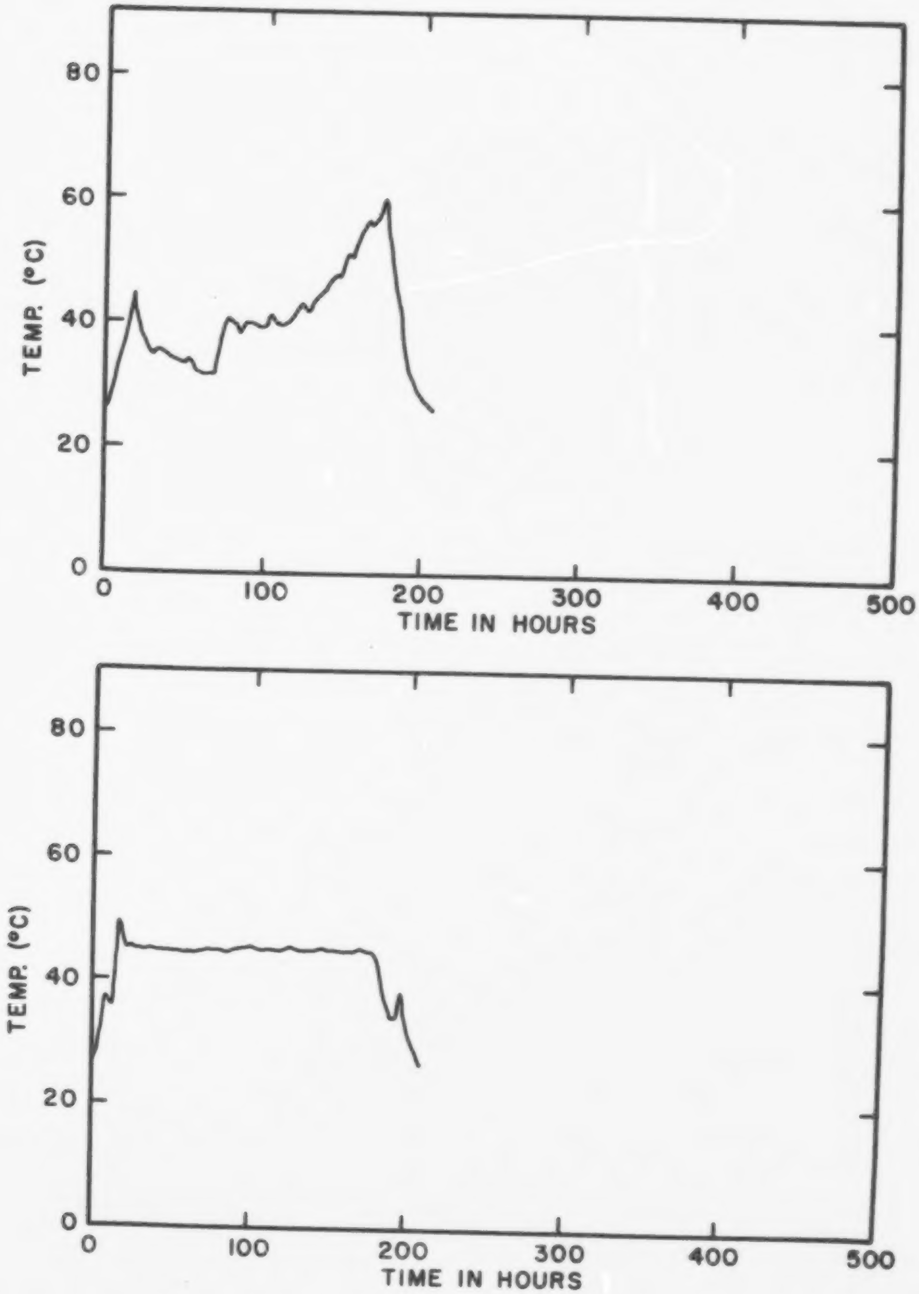


Figure 91. Pile 8, temperature at position 5 (upper plot) and position 6 (lower plot).

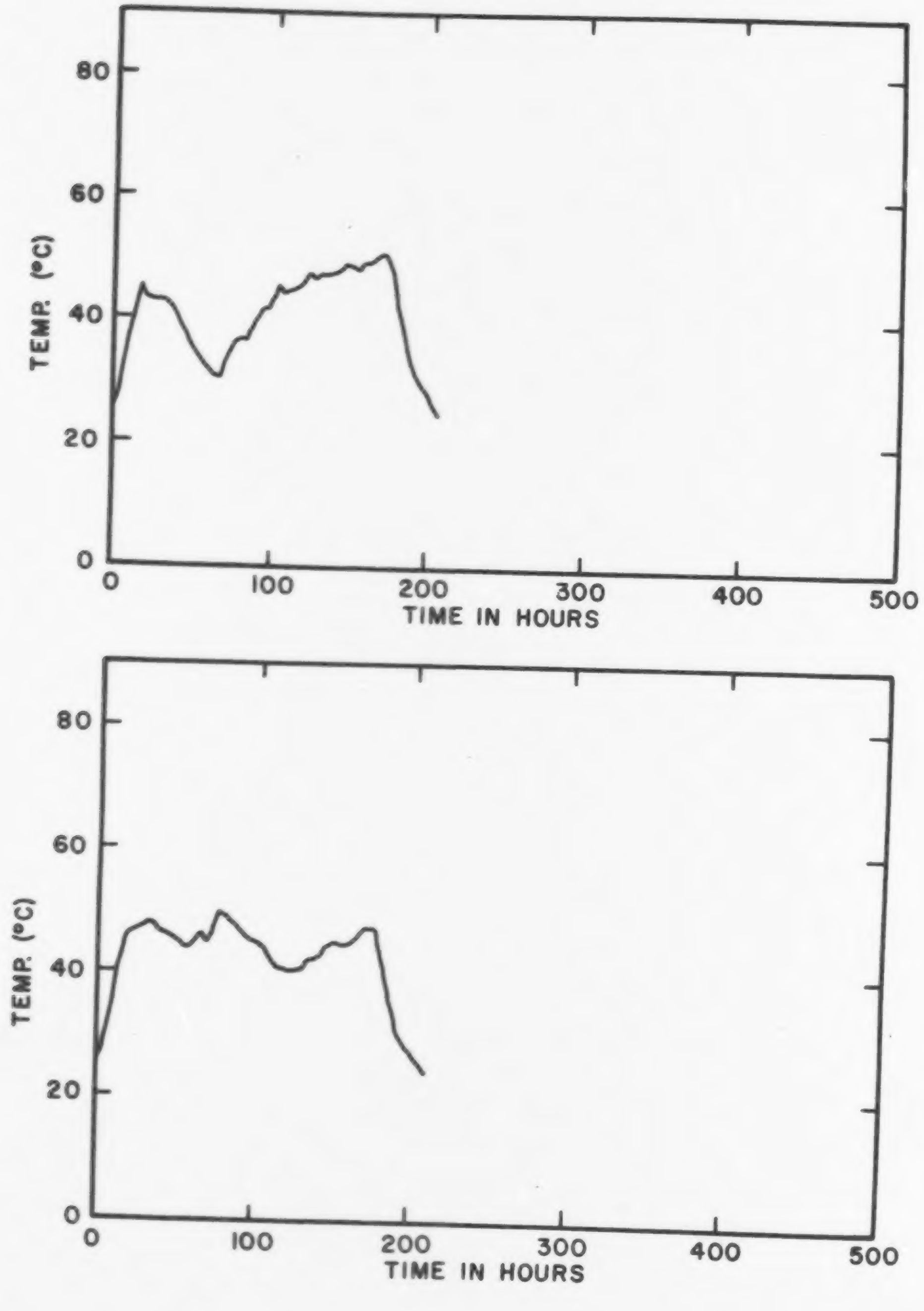


Figure 92. Pile 8, temperature at position 7 (upper plot) and position 8 (lower plot).

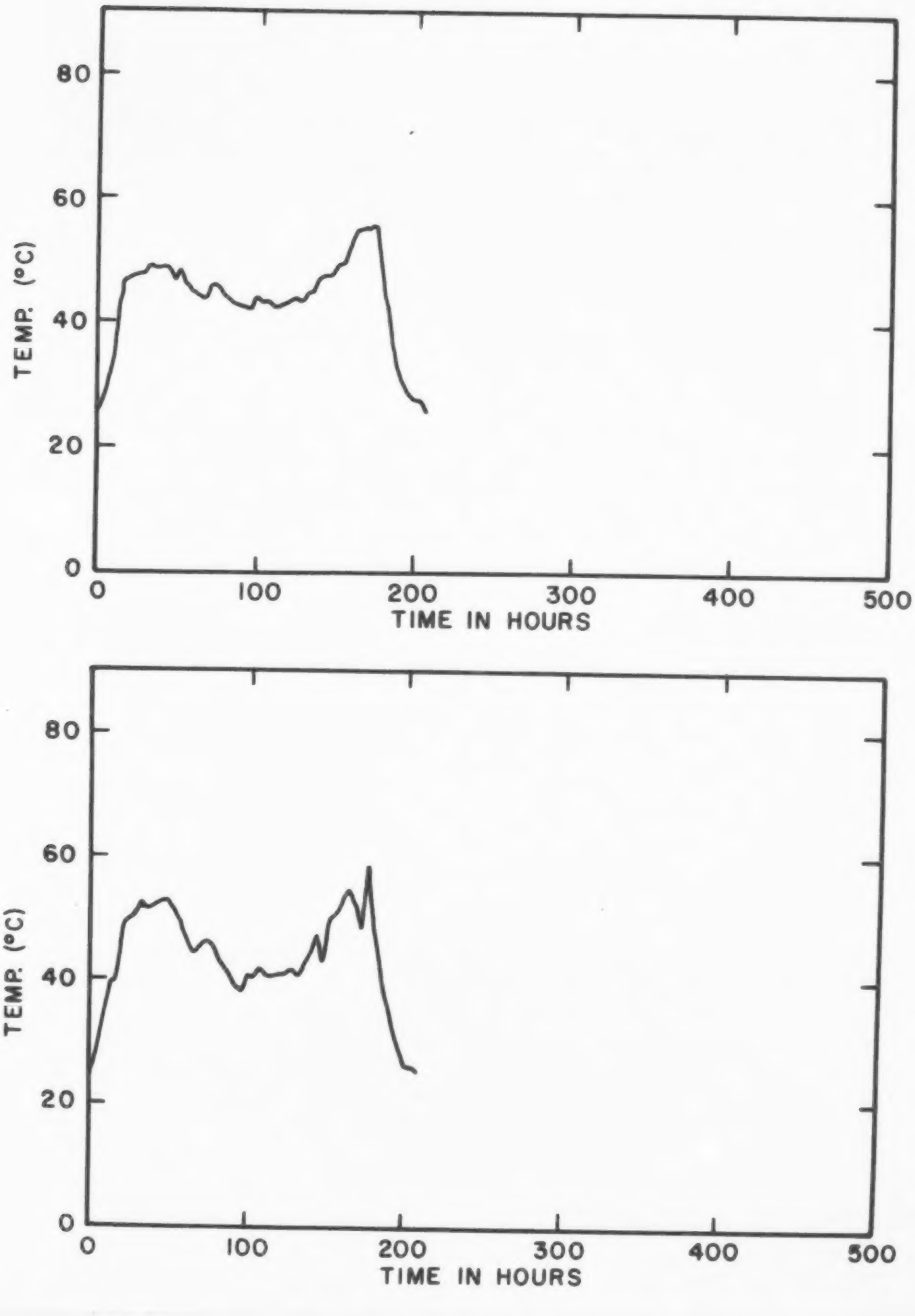


Figure 93. Pile 8, temperature at position 9 (upper plot) and position 10 (lower plot).

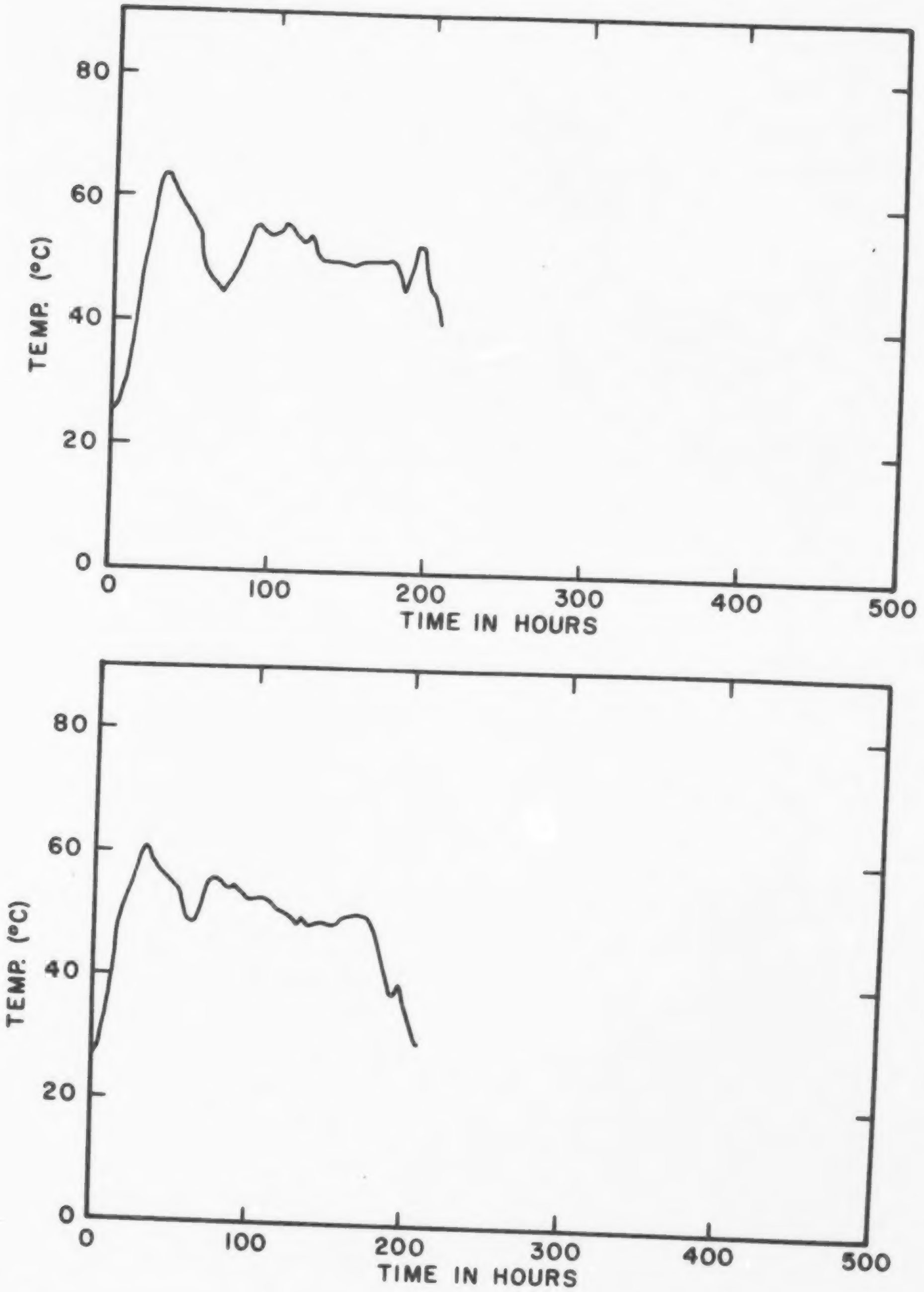
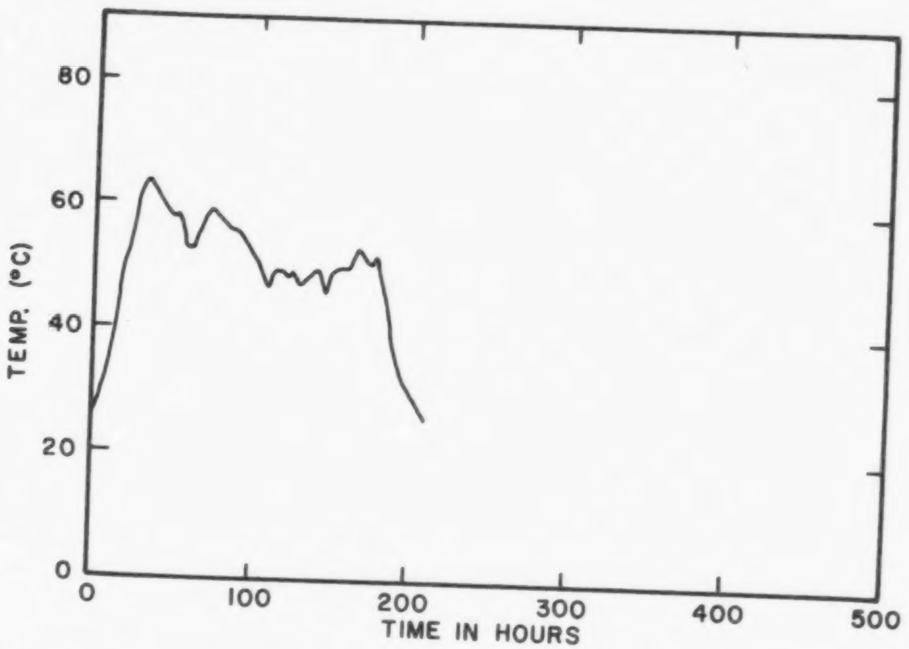


Figure 94. Pile 8, temperature at position 11 (upper plot) and position 12 (lower plot).



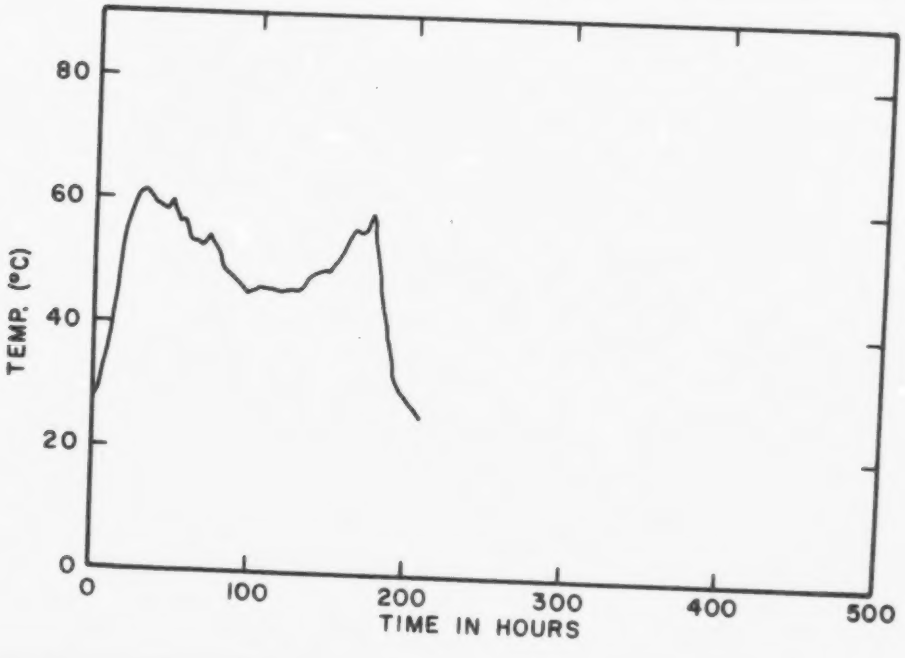


Figure 95. Pile 8, temperature at position 13 (upper plot) and position 14 (lower plot).

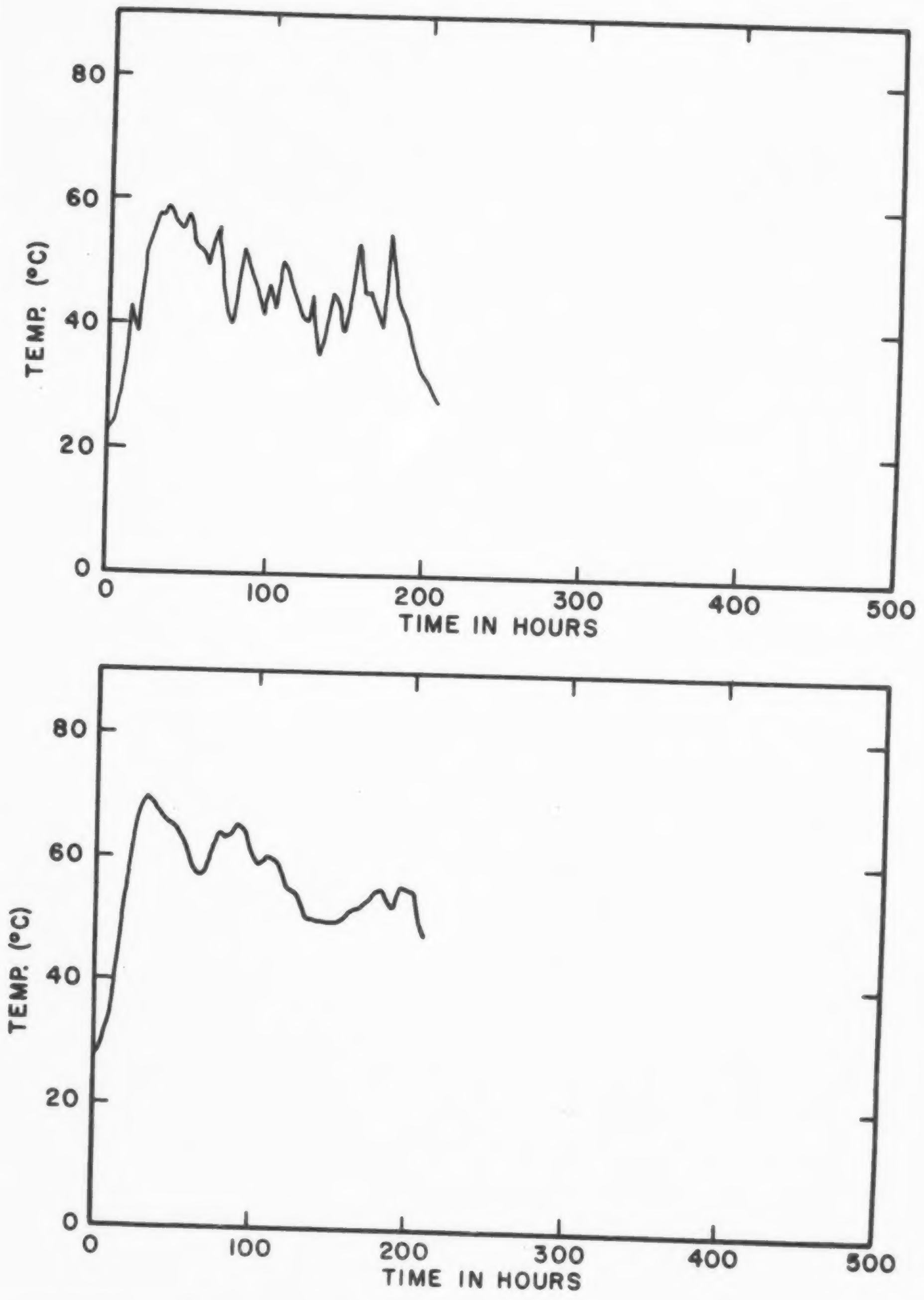


Figure 96. Pile 8, temperature at position 15 (upper plot) and position 16 (lower plot).

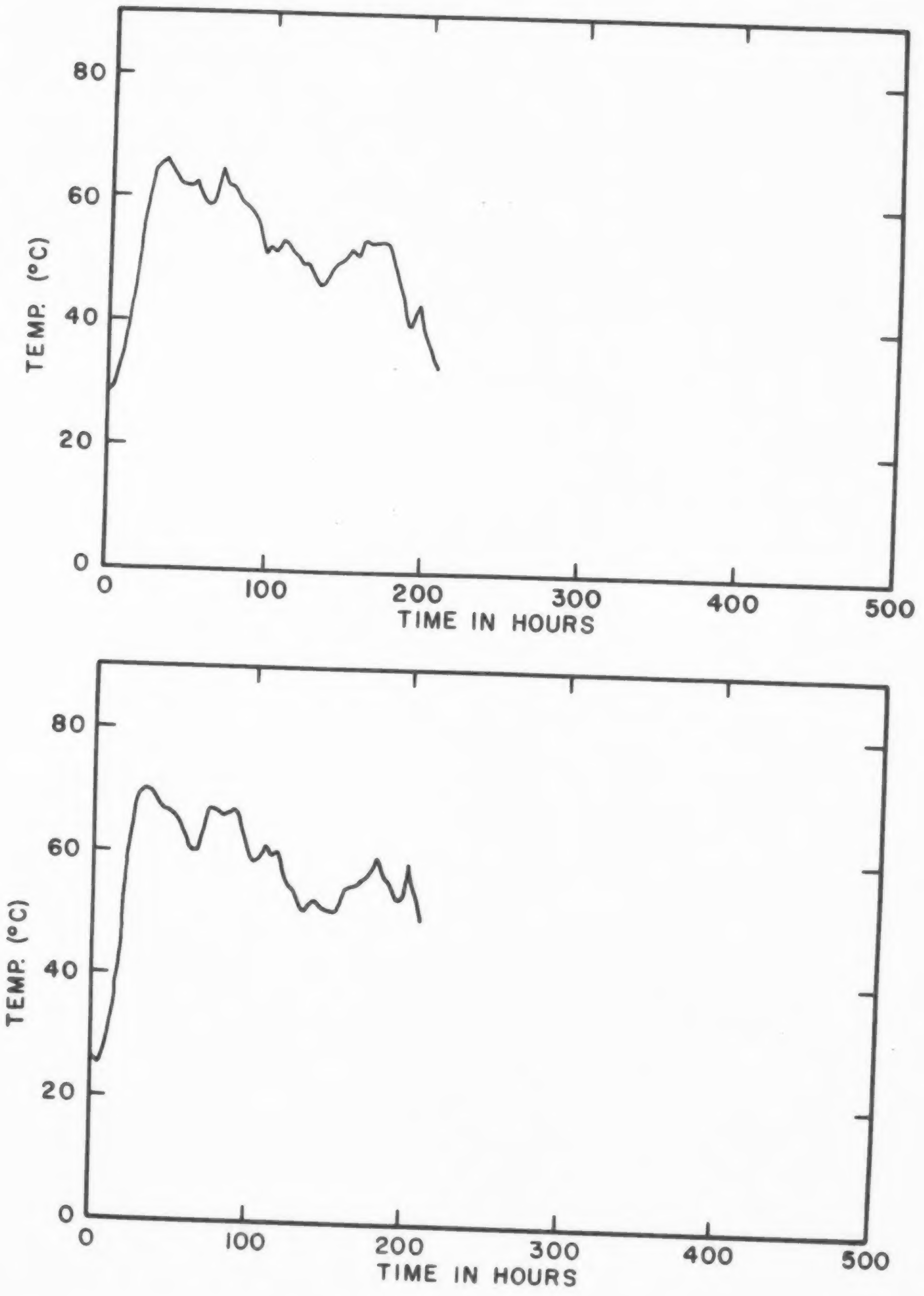


Figure 97. Pile 8, temperature at position 17 (upper plot) and position 18 (lower plot).

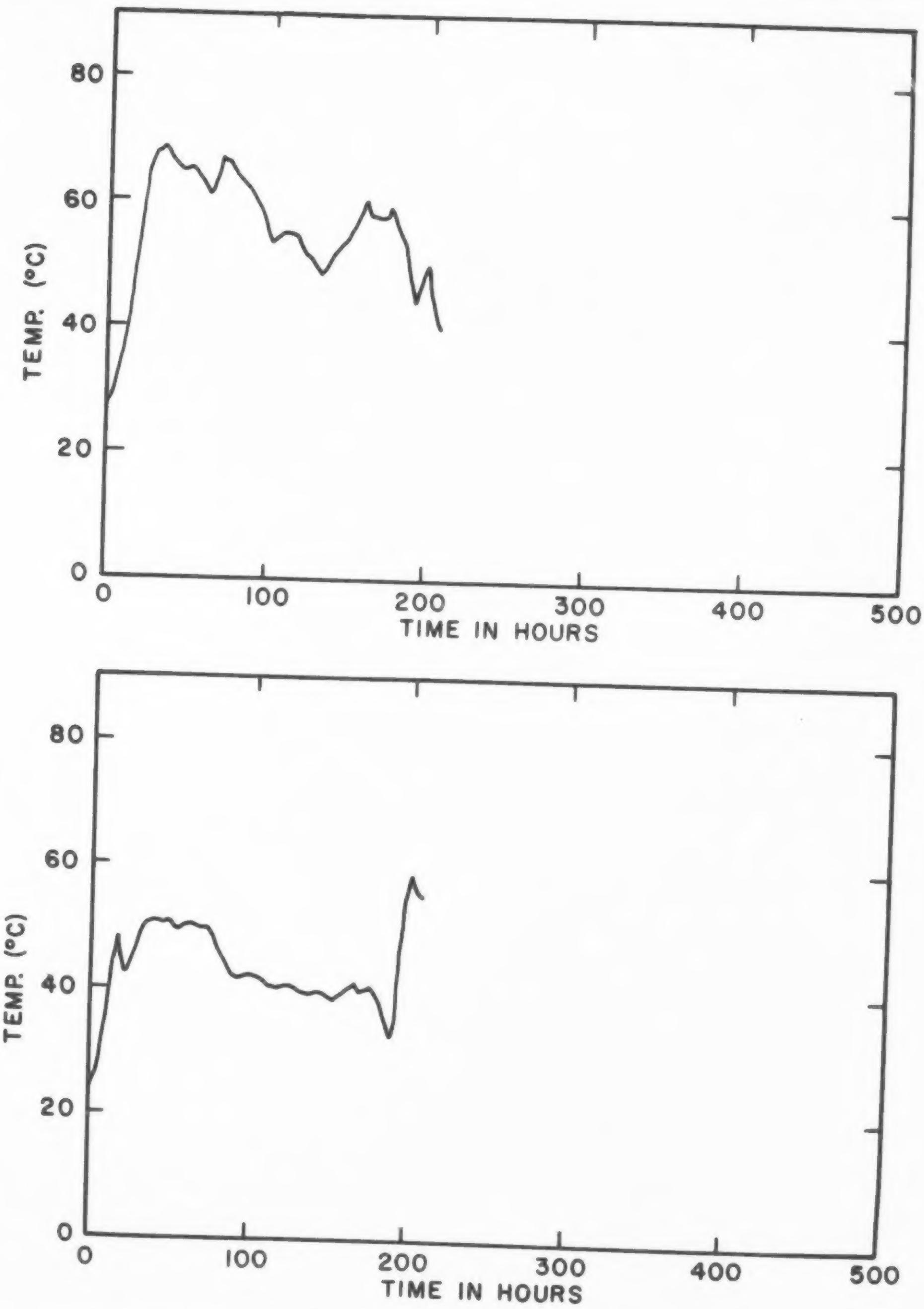
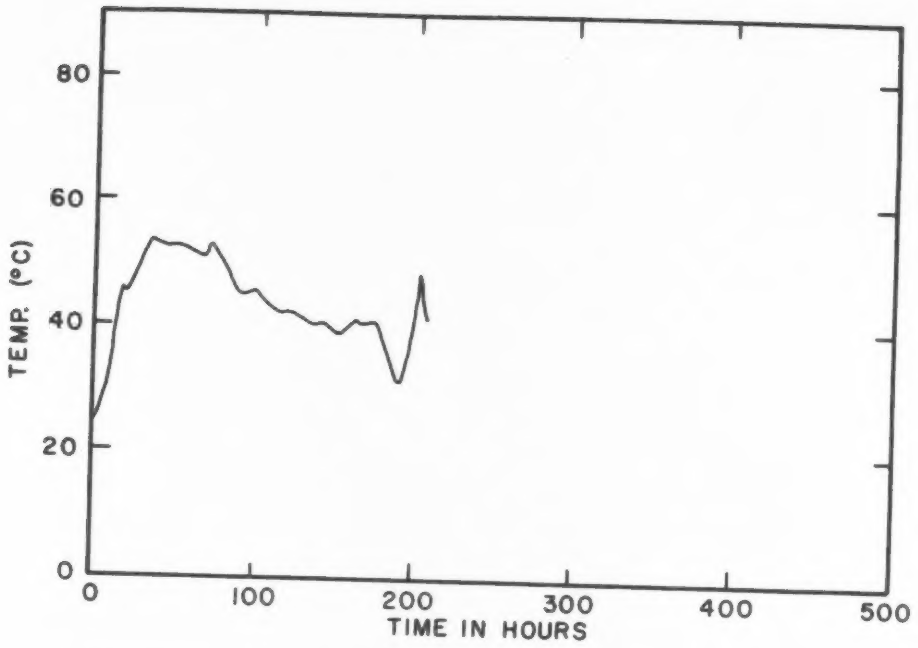


Figure 98. Pile 8, temperature at position 19 (upper plot) and position 20 (lower plot).



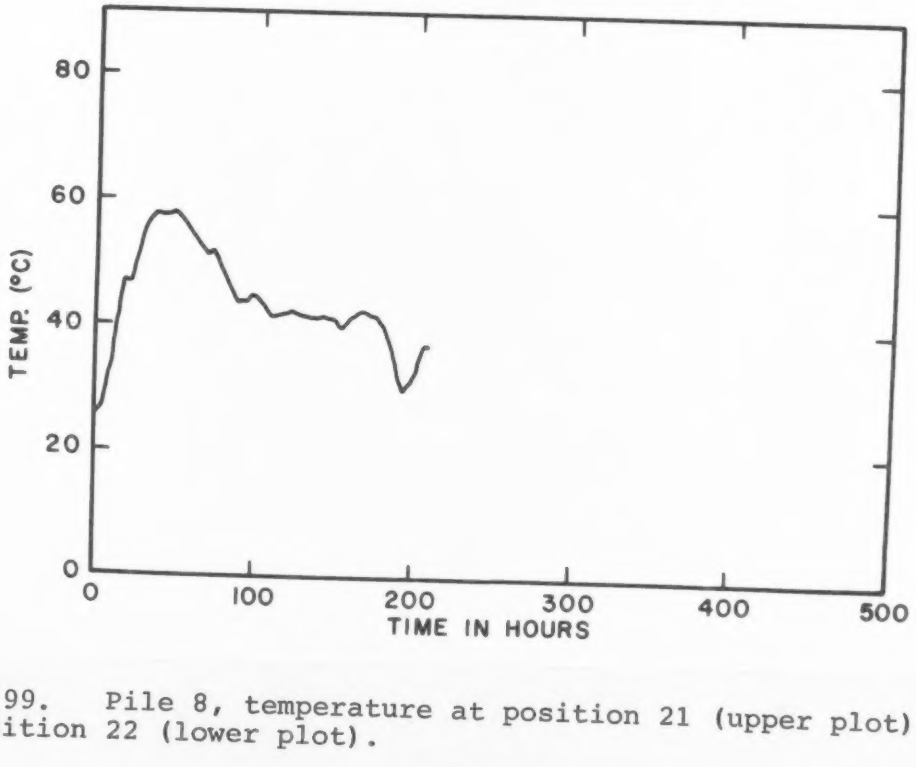
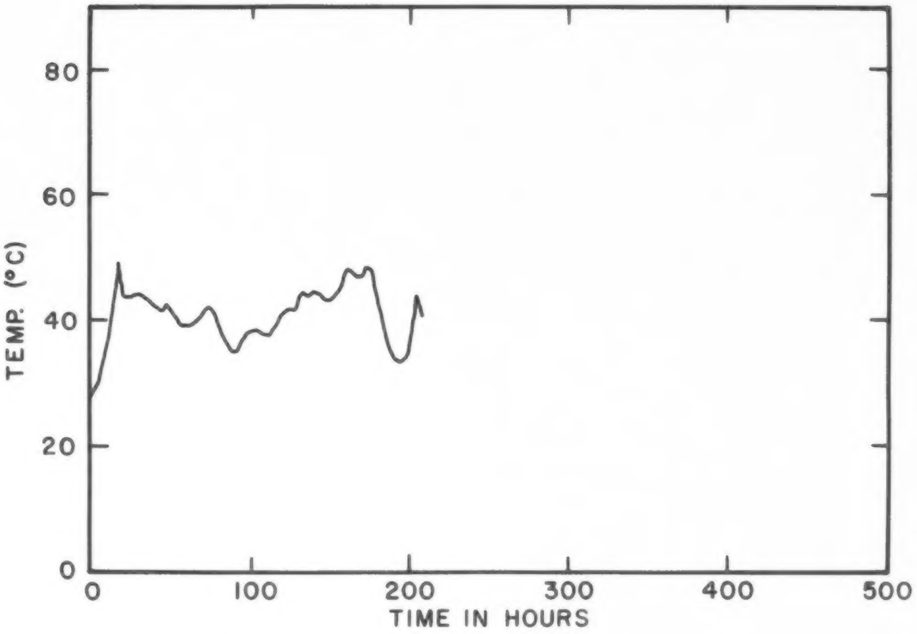


Figure 99. Pile 8, temperature at position 21 (upper plot) and position 22 (lower plot).



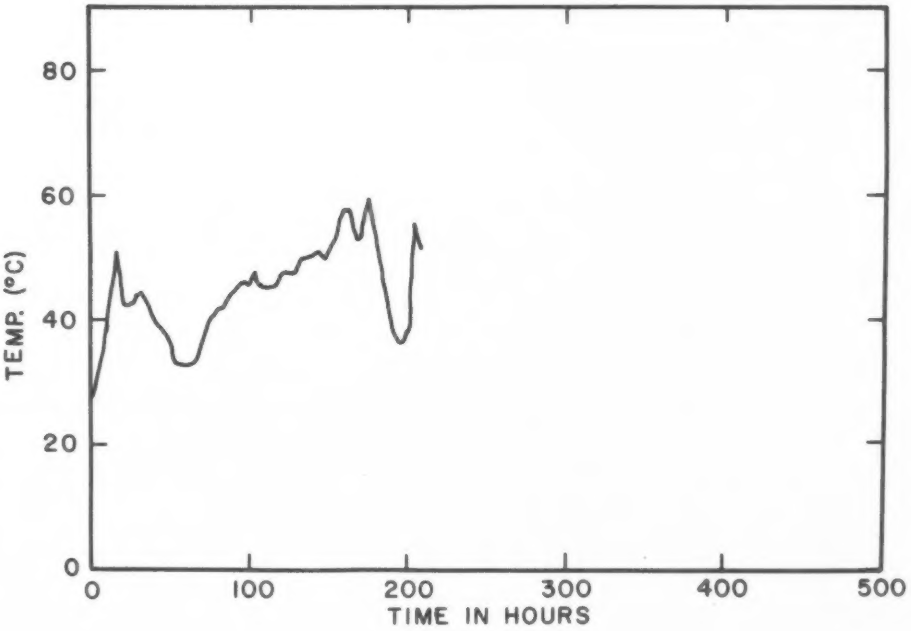


Figure 100. Pile 8, temperature at position 23 (upper plot) and position 24 (lower plot).

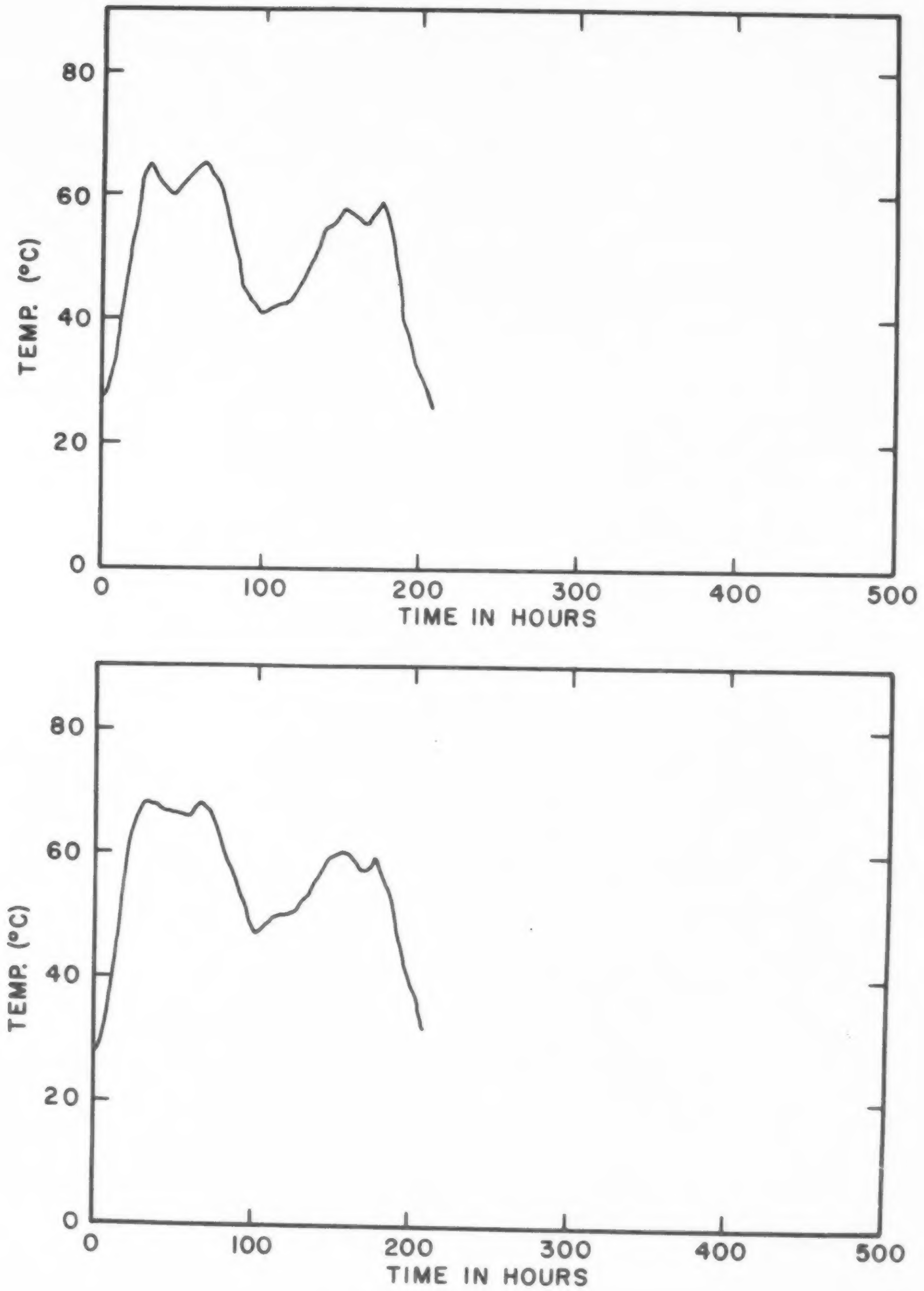


Figure 101. Pile 8, temperature at position 25 (upper plot) and position 26 (lower plot).

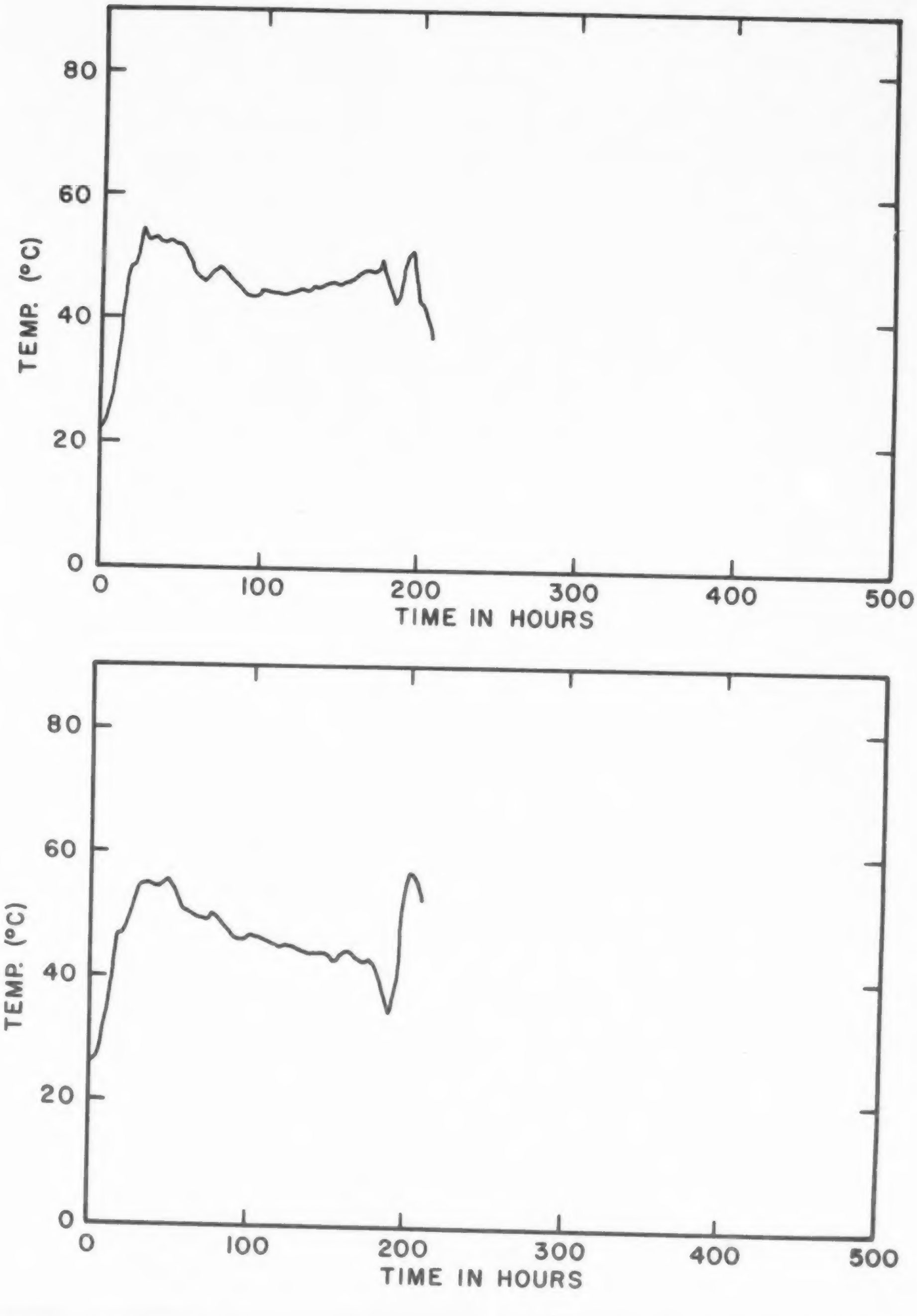


Figure 102. Pile 8, temperature at position 27 (upper plot) and position 28 (lower plot).

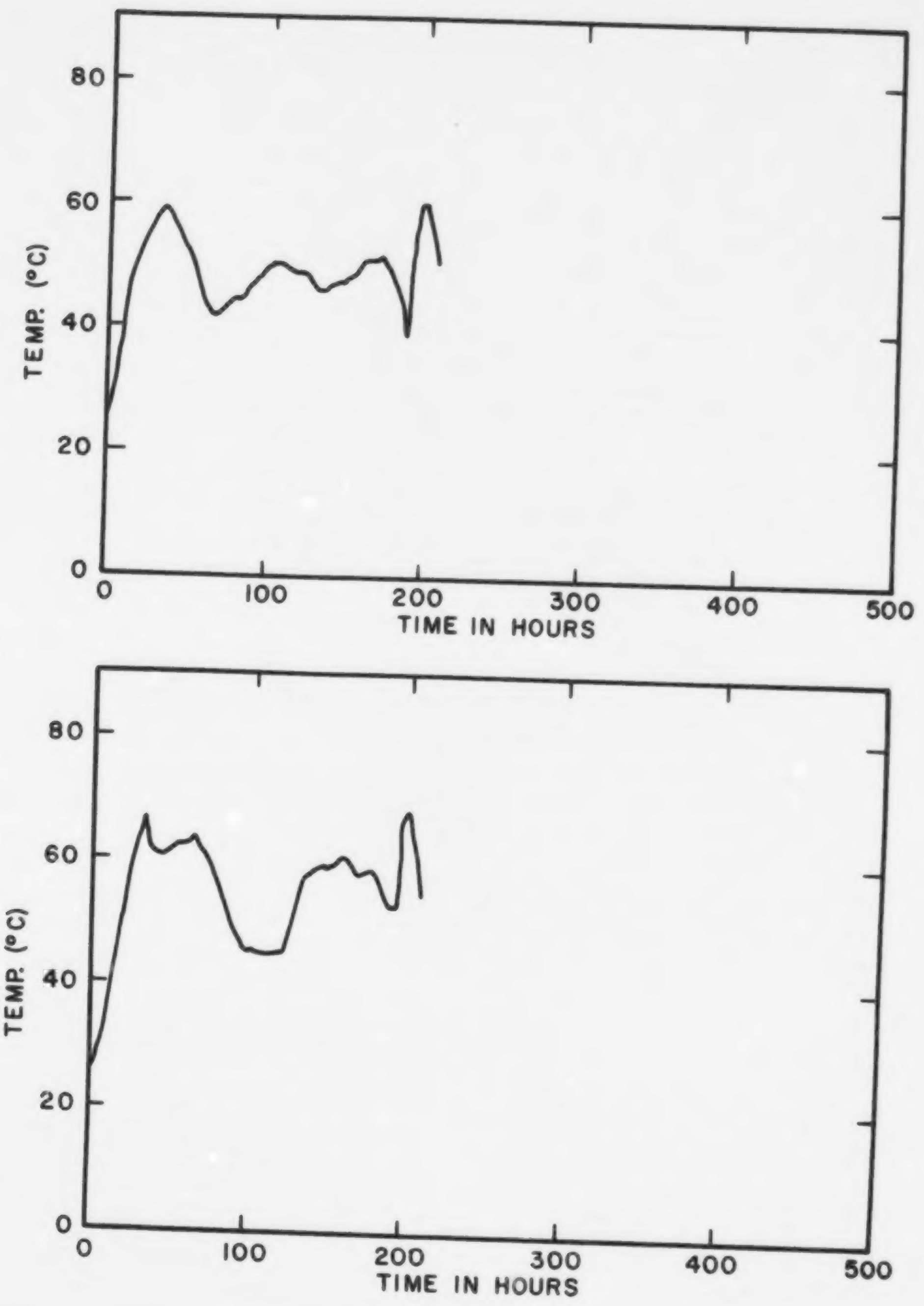


Figure 103. Pile 8, temperature at position 29 (upper plot) and position 30 (lower plot).

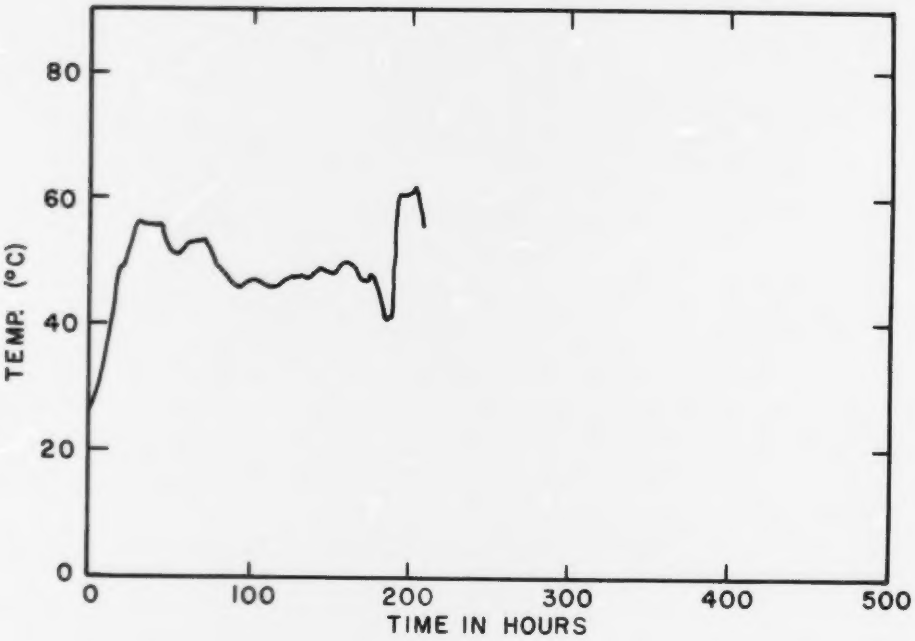


Figure 104. Pile 8, temperature at position 31.

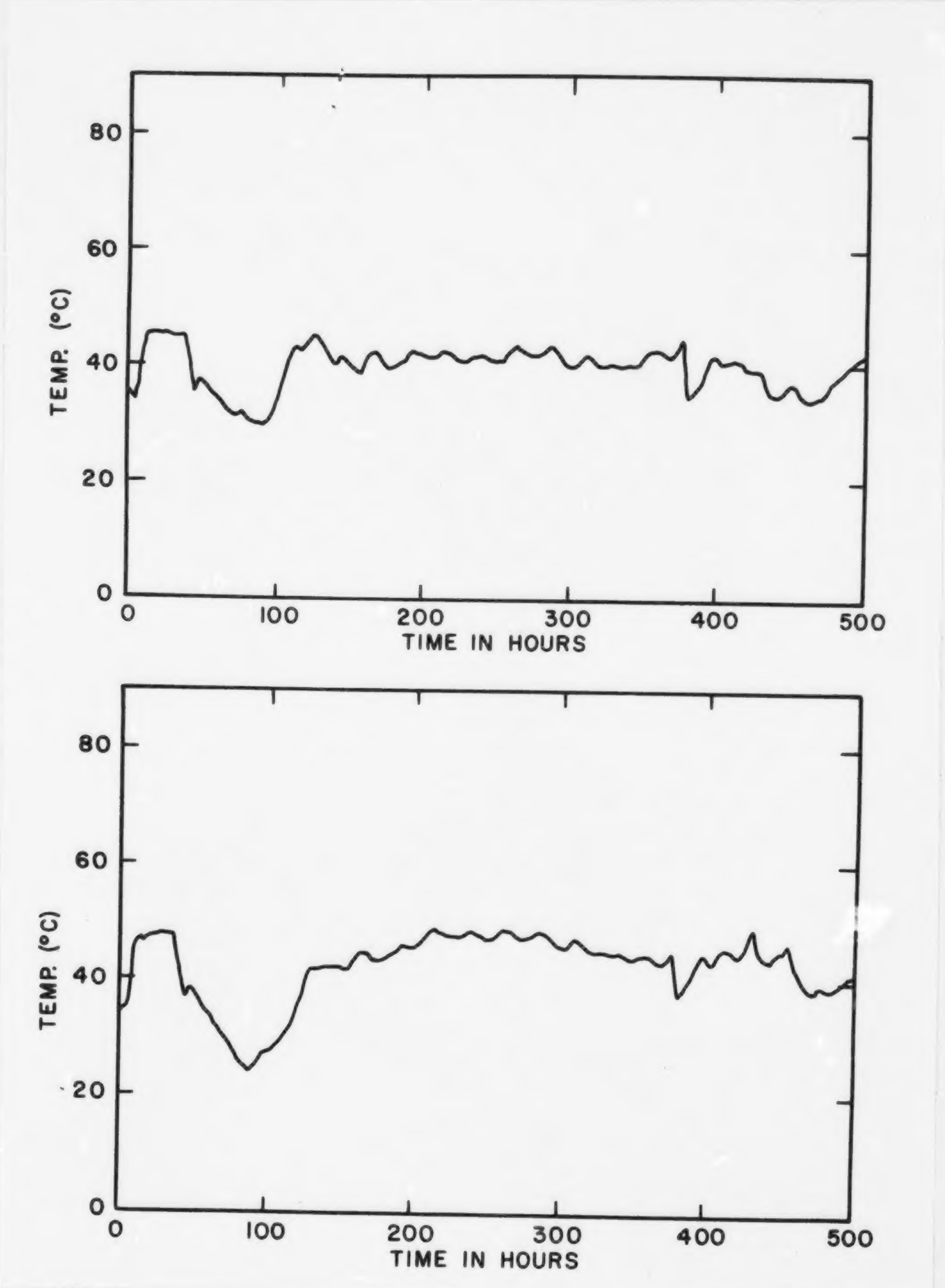


Figure 105. Pile 9A, temperature at position 1 (upper plot) and position 2 (lower plot).

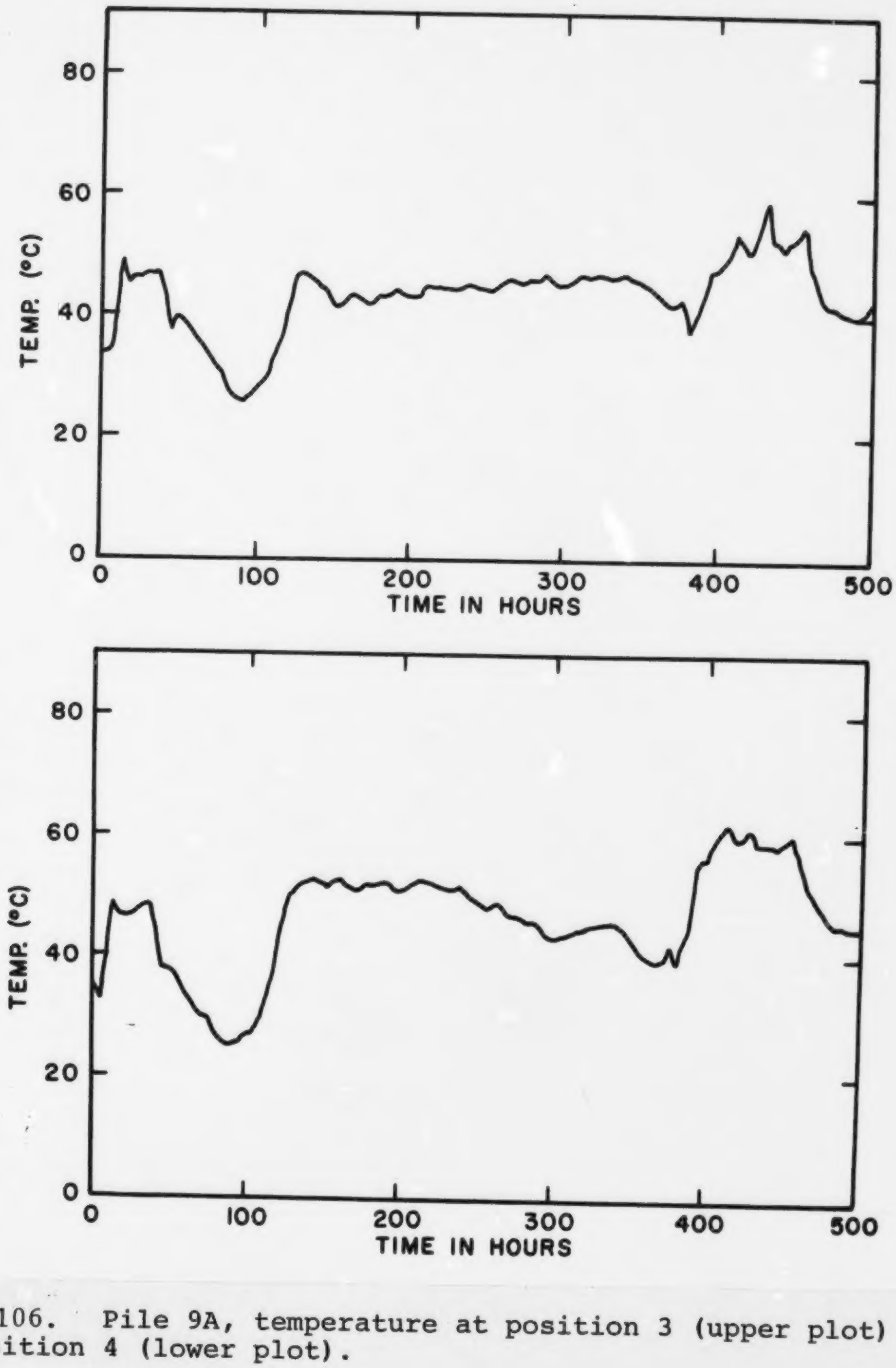


Figure 106. Pile 9A, temperature at position 3 (upper plot) and position 4 (lower plot).

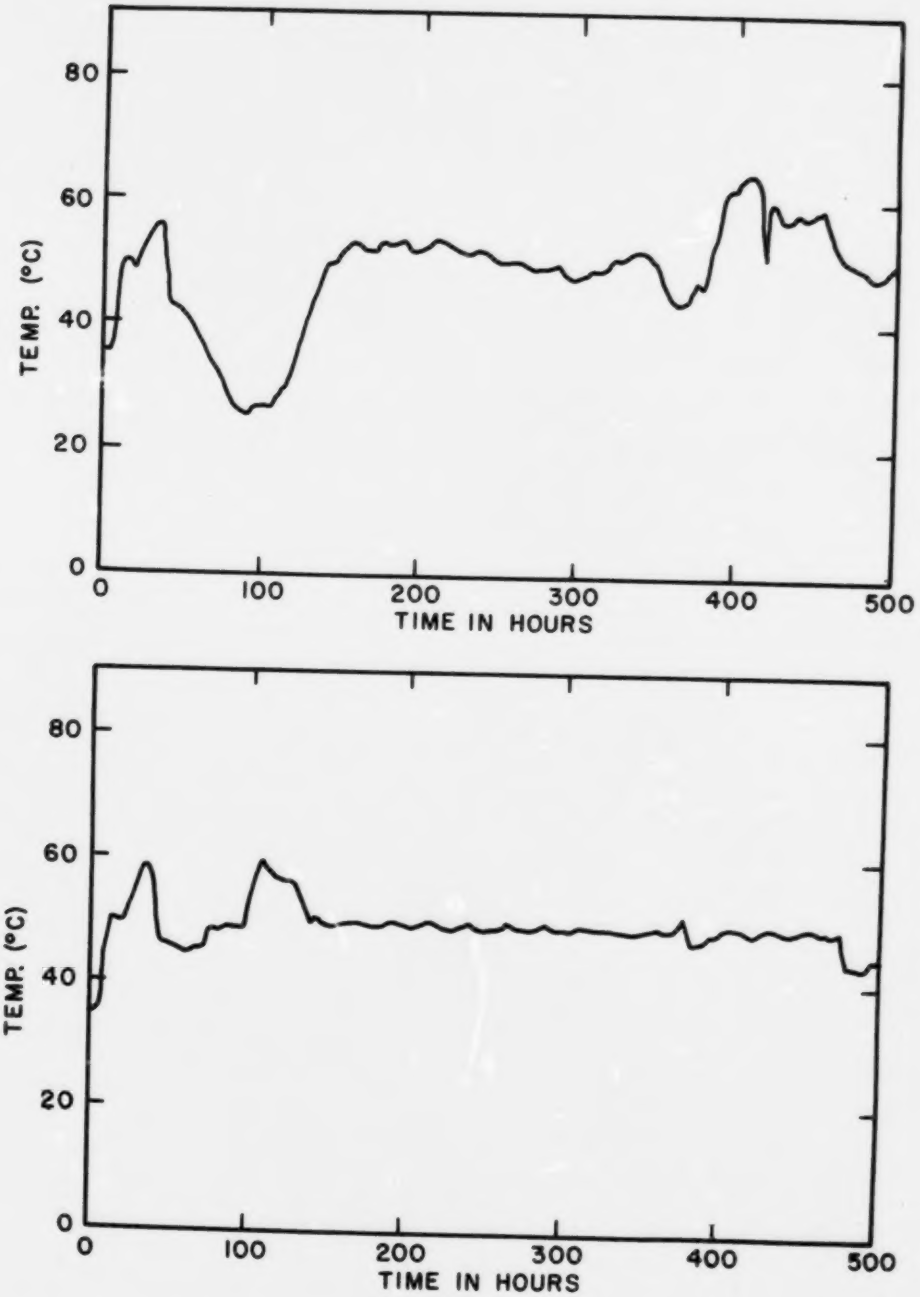


Figure 107. Pile 9A, temperature at position 5 (upper plot) and position 6 (lower plot).

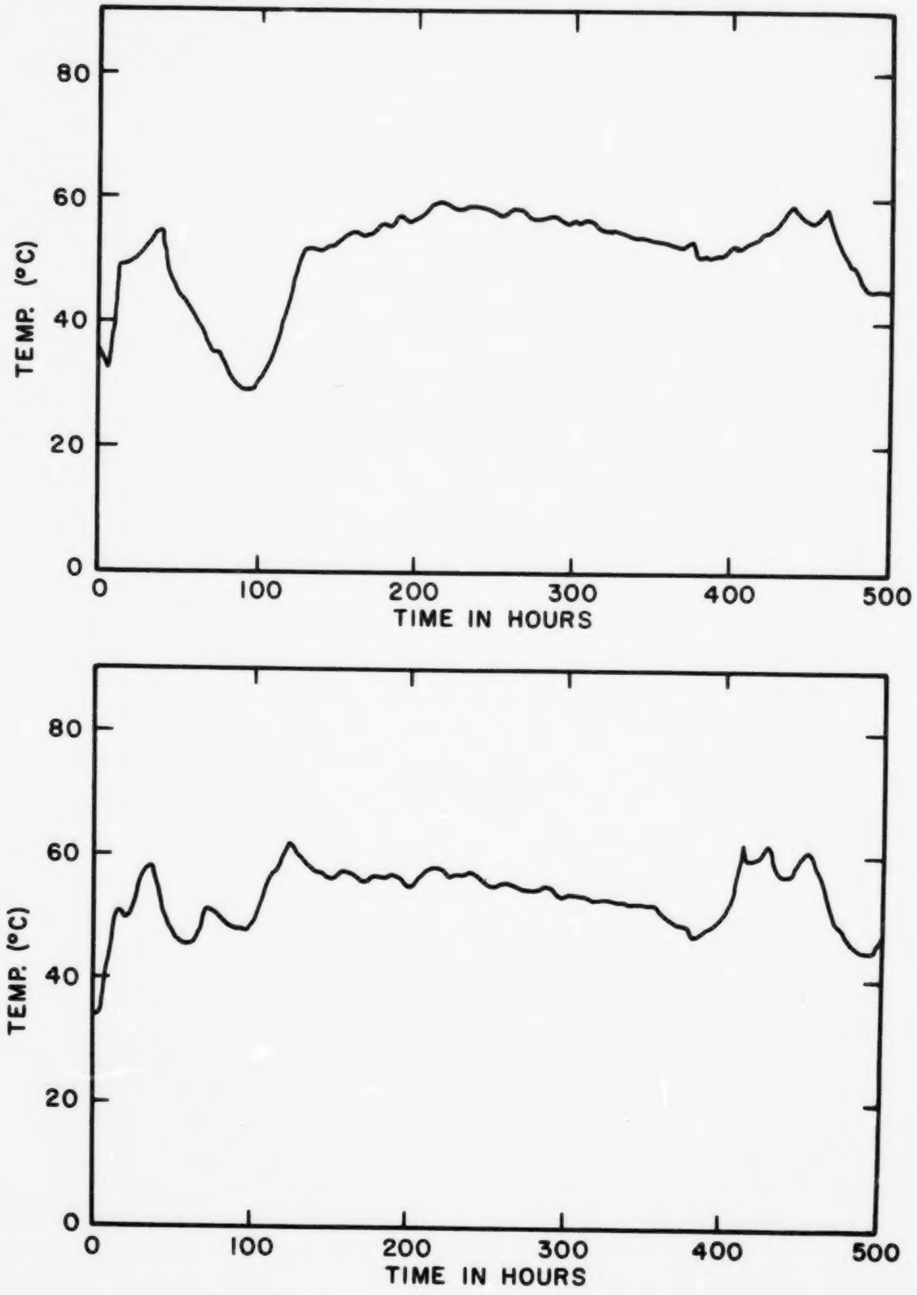


Figure 108. Pile 9A, temperature at position 7 (upper plot) and position 8 (lower plot).

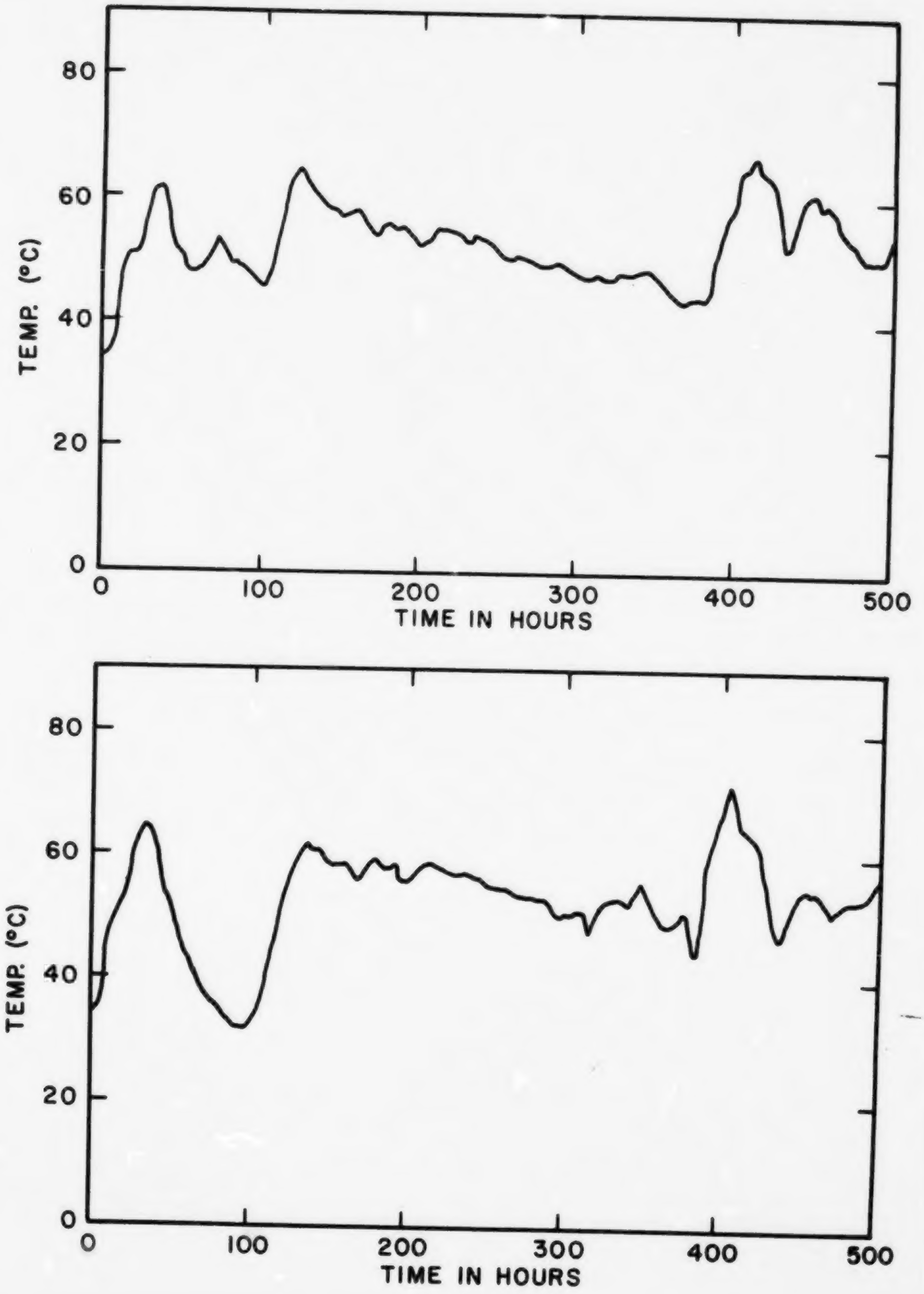


Figure 109. Pile 9A, temperature at position 9 (upper plot) and position 10 (lower plot).

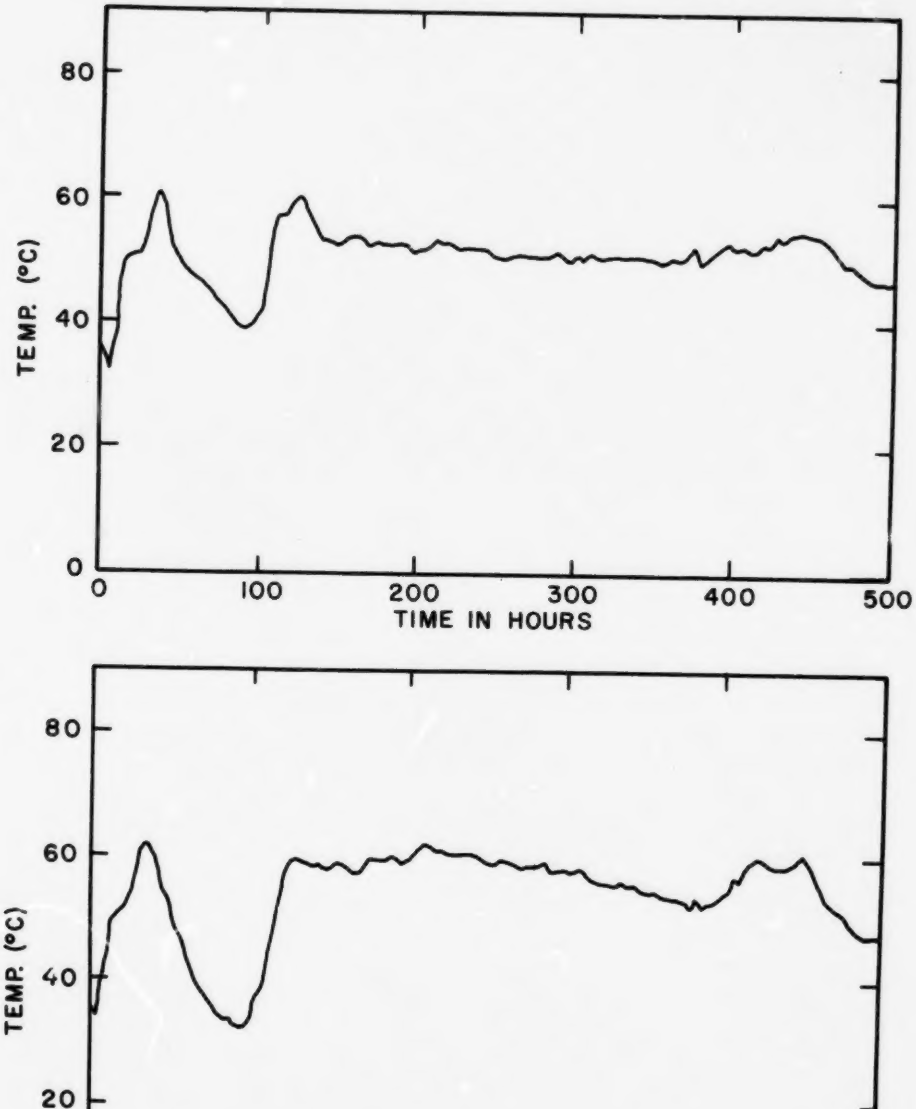


Figure 110. Pile 9A, temperature at position 11 (upper plot) and position 12 (lower plot).

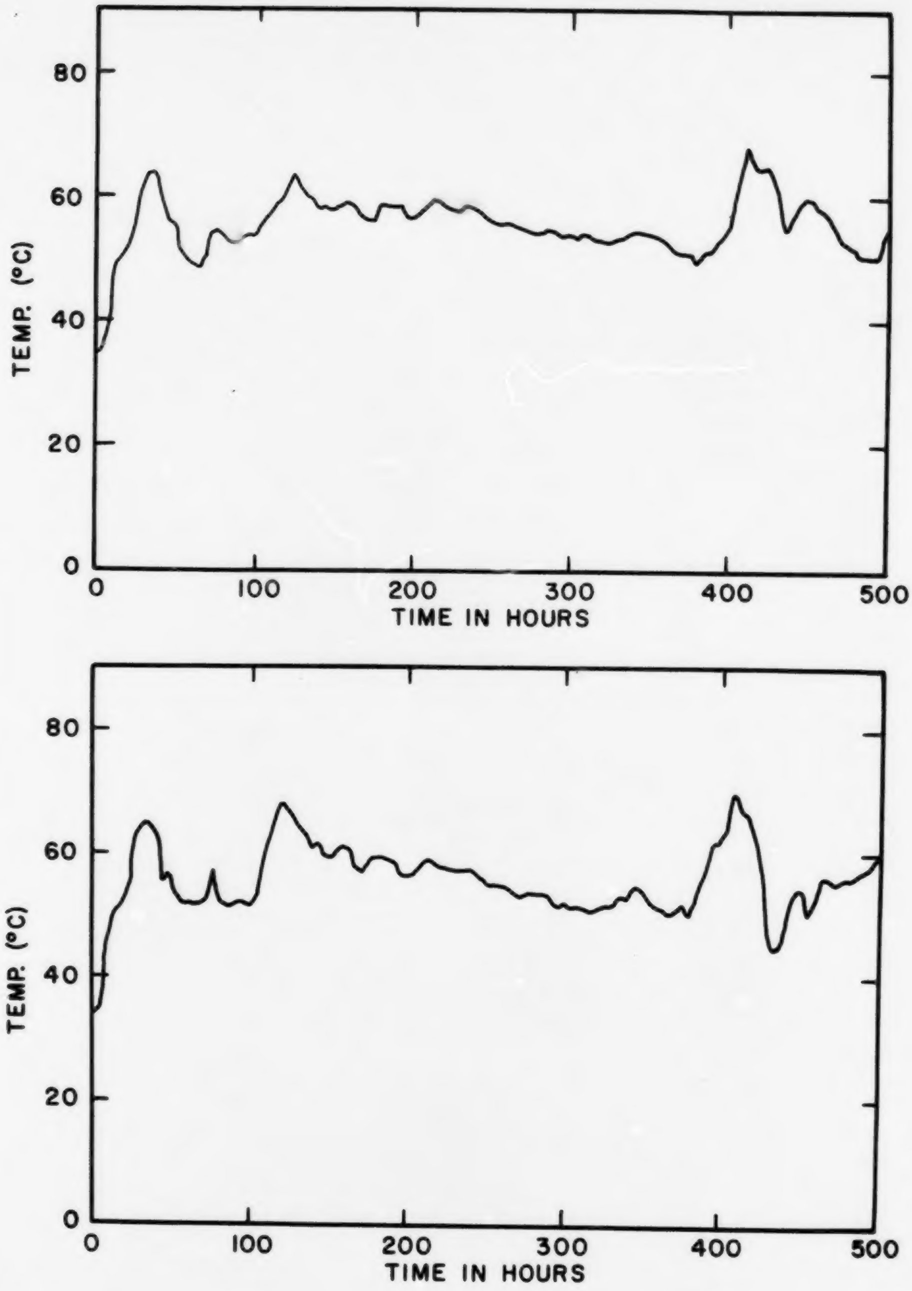


Figure 111. Pile 9A, temperature at position 13 (upper plot) and position 14 (lower plot).

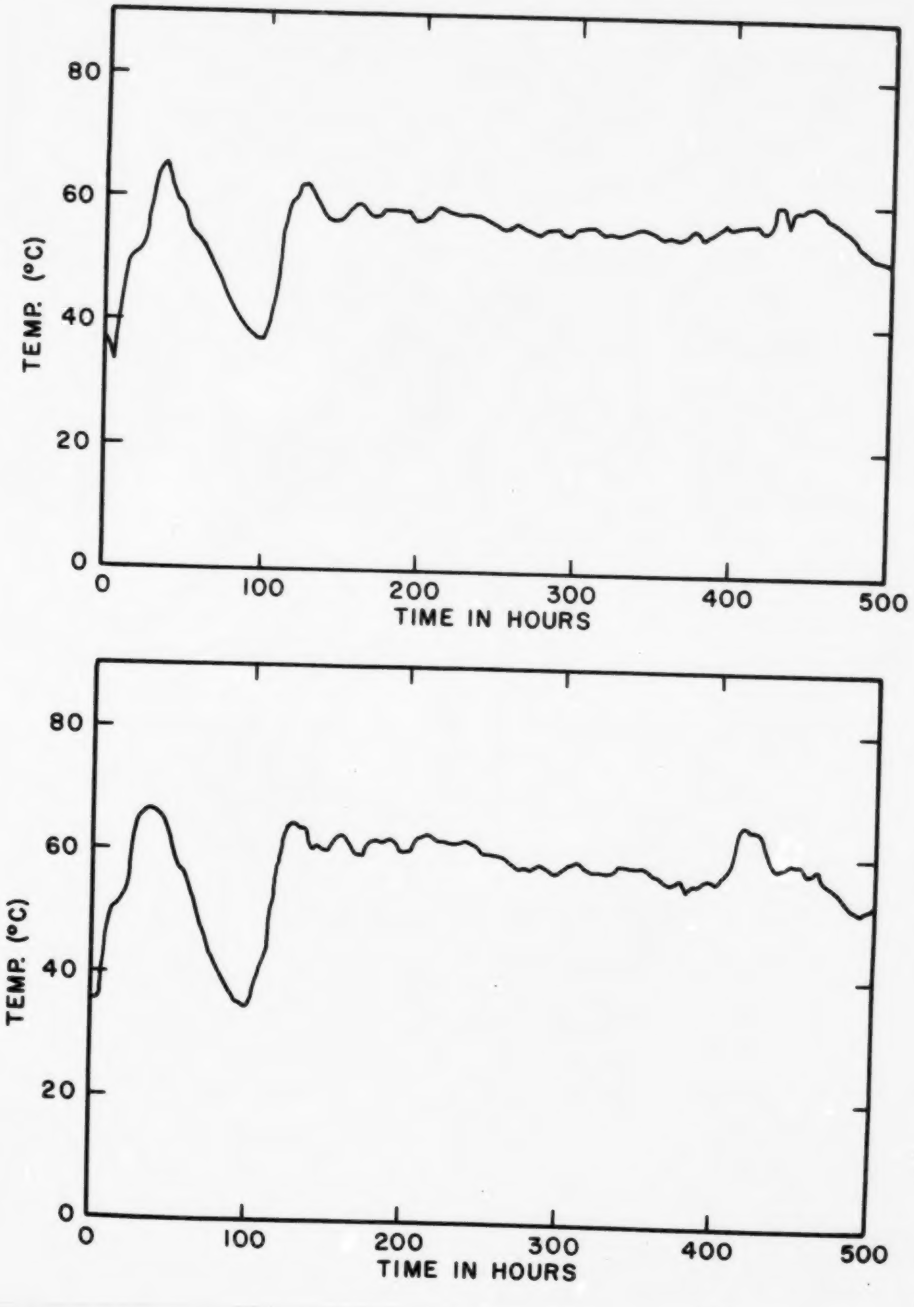


Figure 112. Pile 9A, temperature at position 15 (upper plot) and position 16 (lower plot).

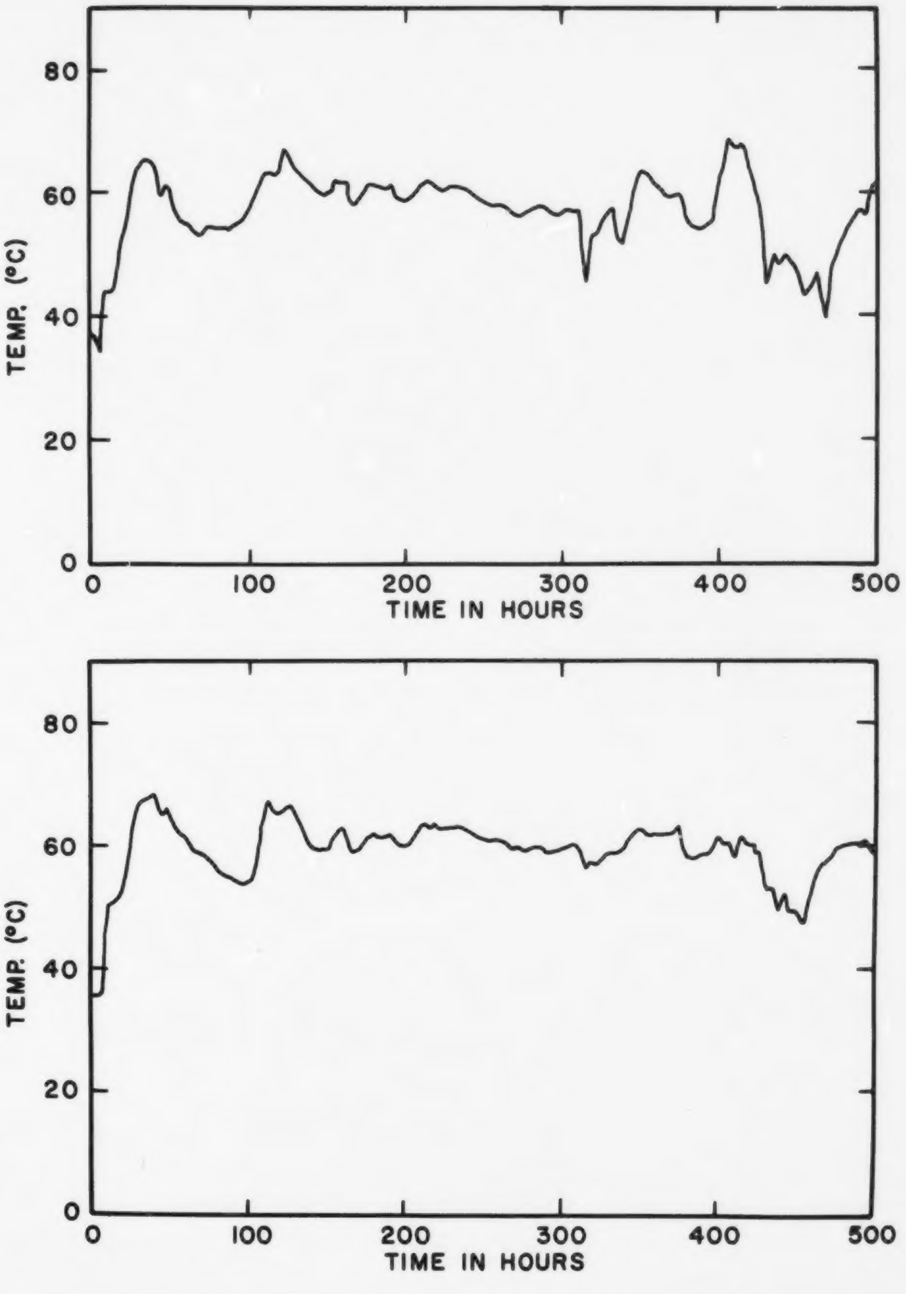


Figure 113. Pile 9A, temperature at position 17 (upper plot) and position 18 (lower plot).

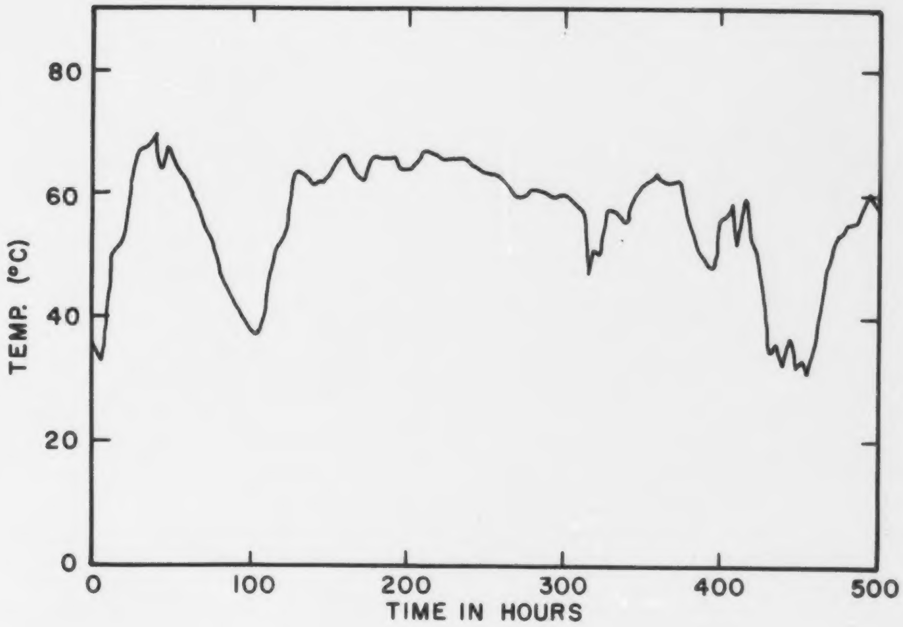


Figure 114. Pile 9A, temperature at position 19.

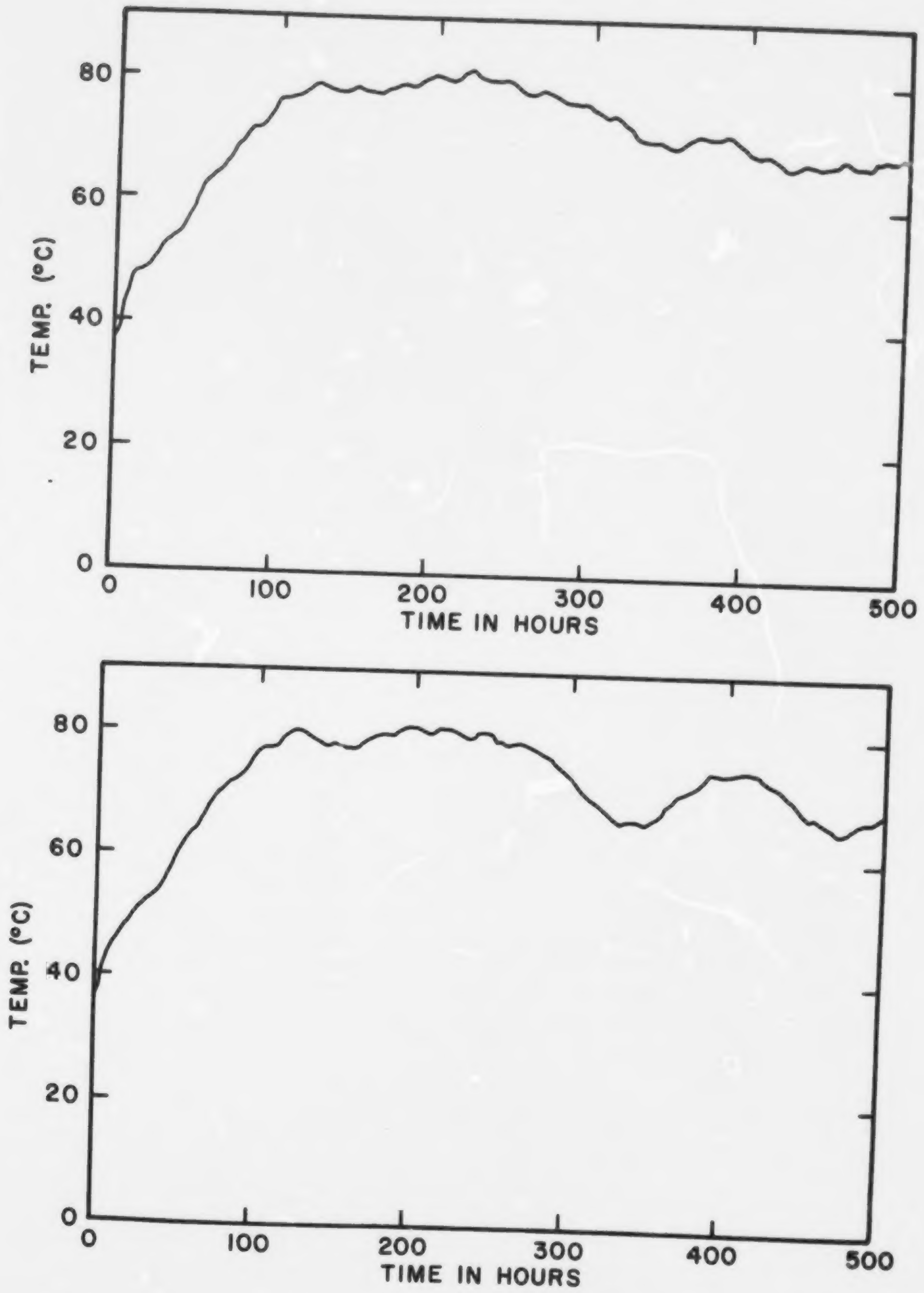


Figure 115. Pile 9B, temperature at position 1 (upper plot) and position 2 (lower plot).

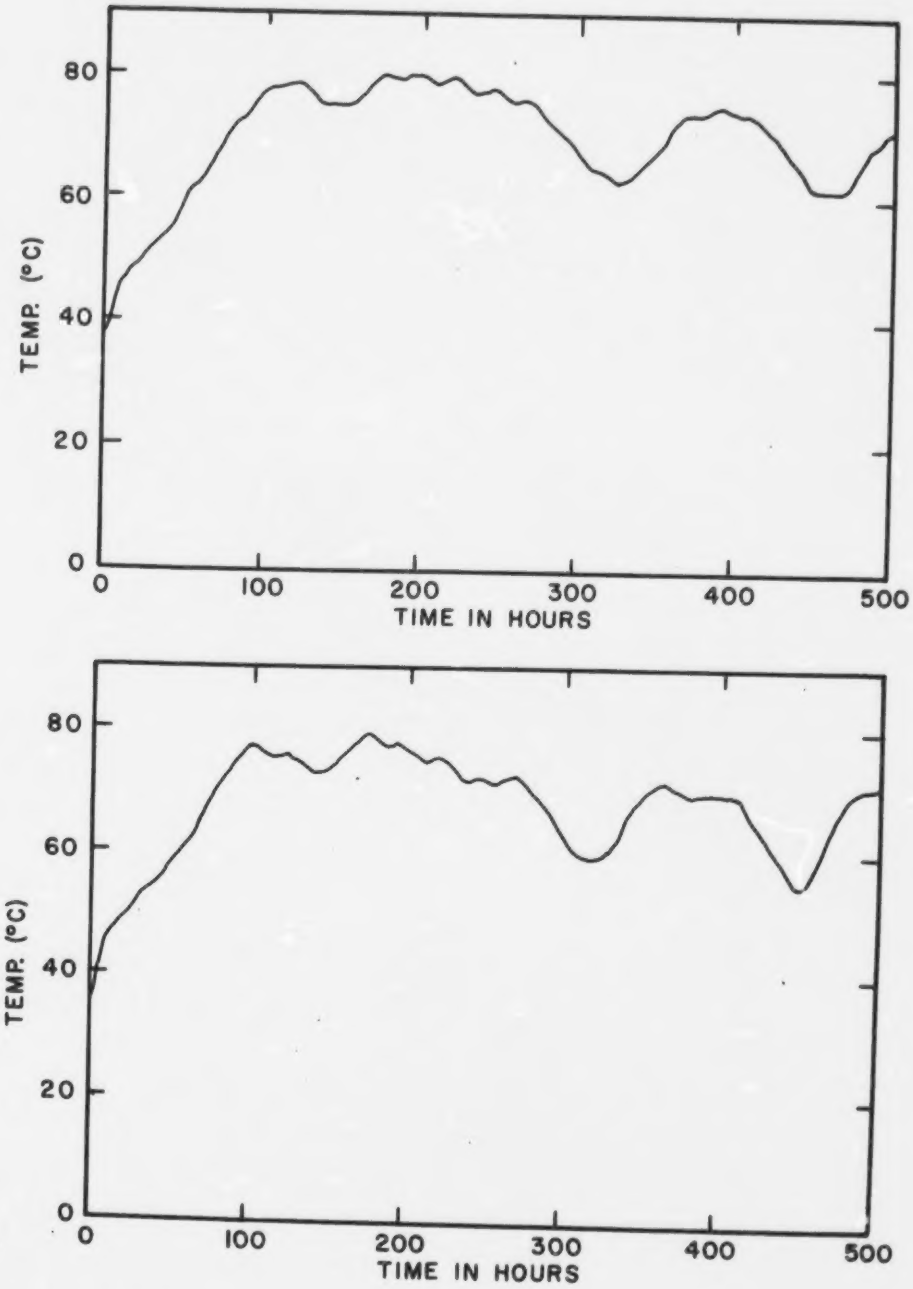


Figure 116. Pile 9B, temperature at position 3 (upper plot) and position 4 (lower plot).

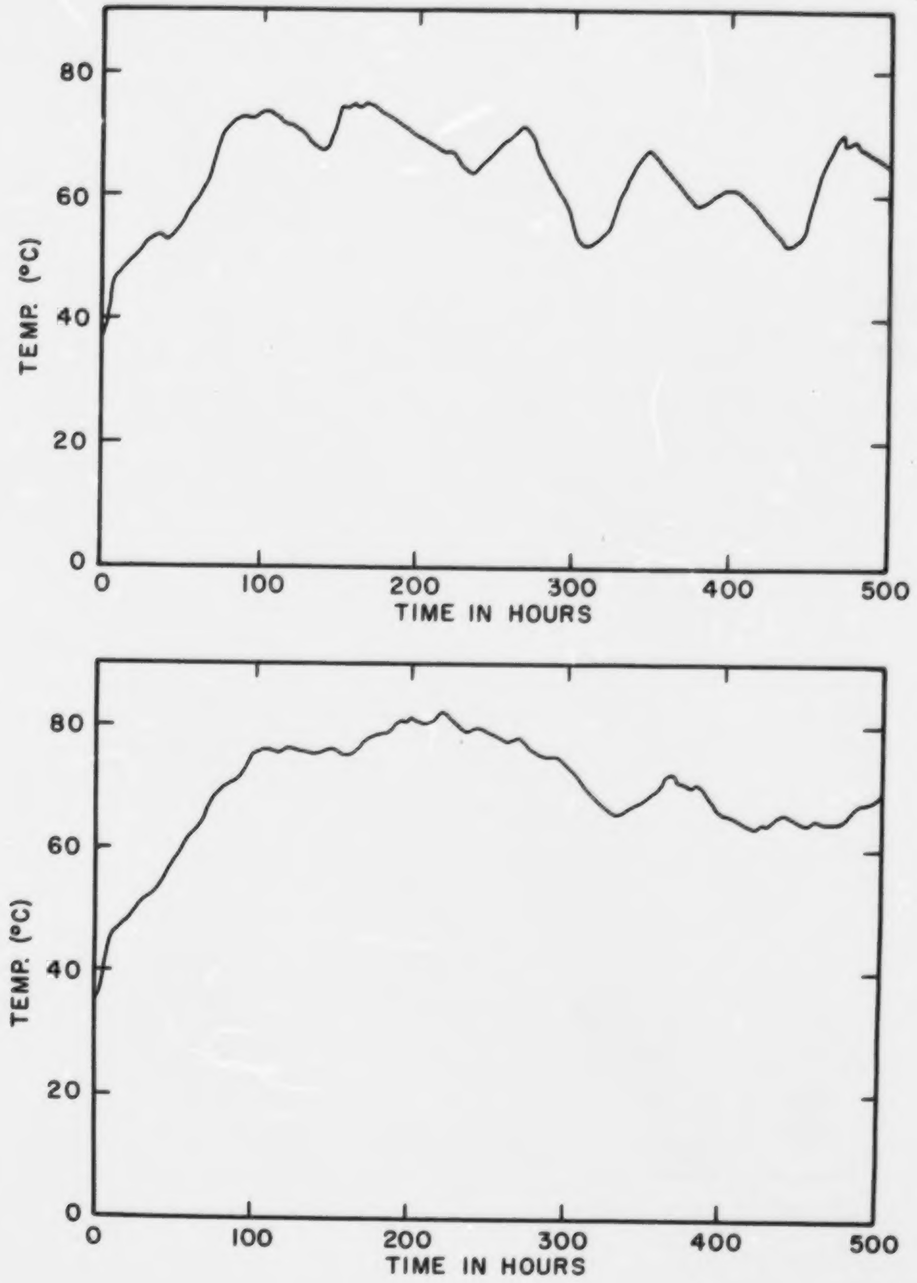


Figure 117. Pile 9B, temperature at position 5 (upper plot) and position 6 (lower plot).

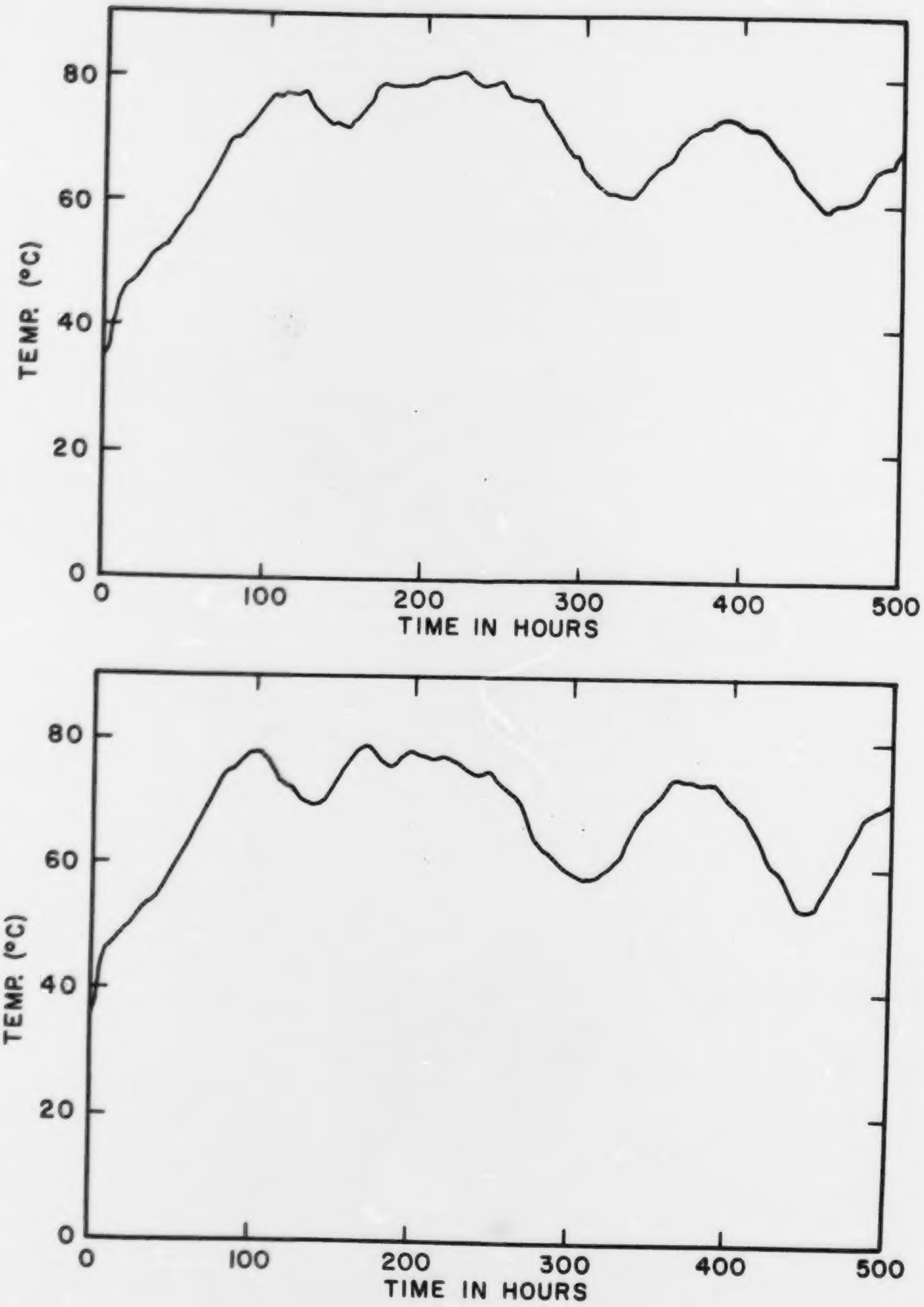


Figure 118. Pile 9B, temperature at position 7 (upper plot) and position 8 (lower plot).

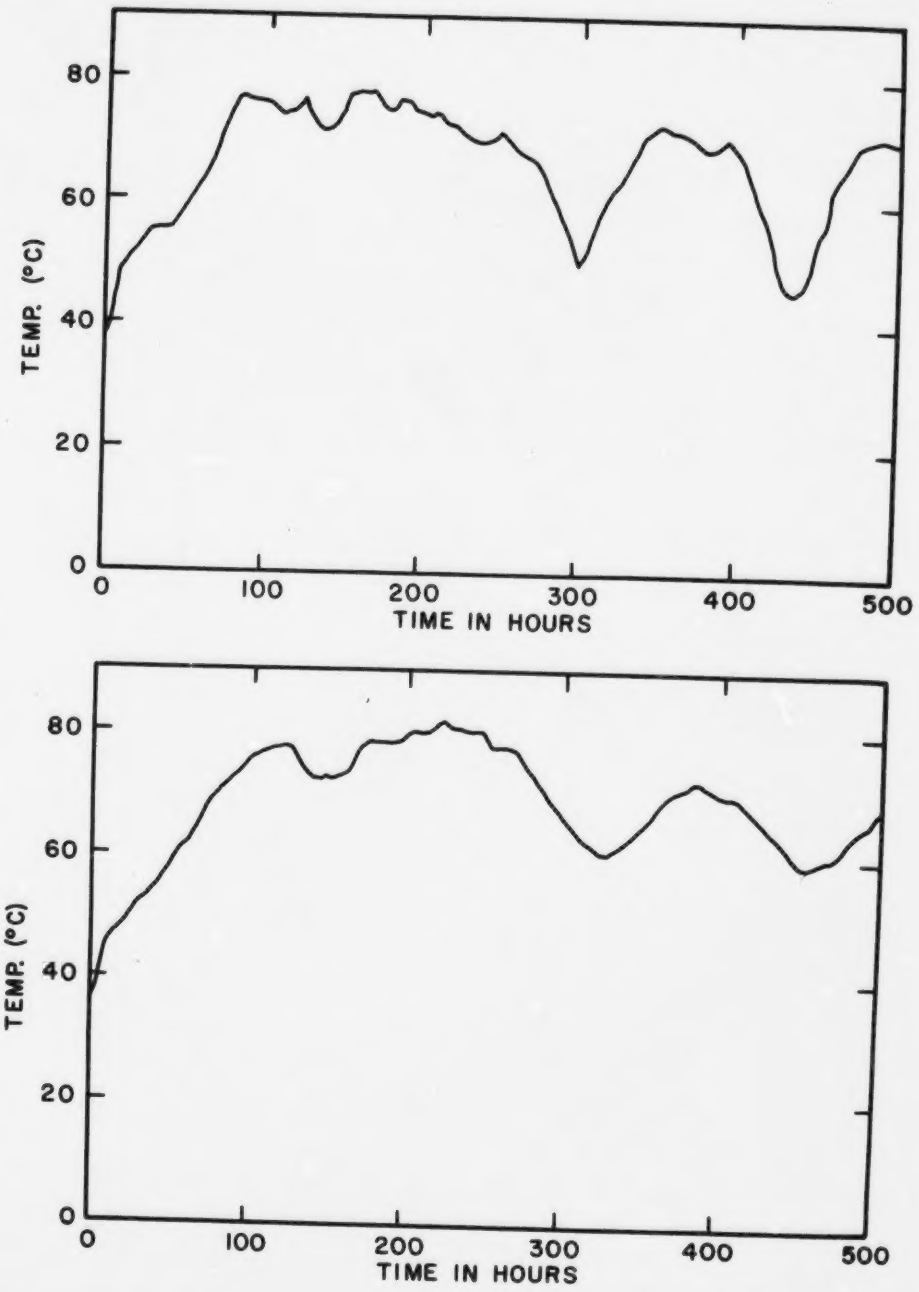


Figure 119. Pile 9B, temperature at position 9 (upper plot) and position 10 (lower plot).

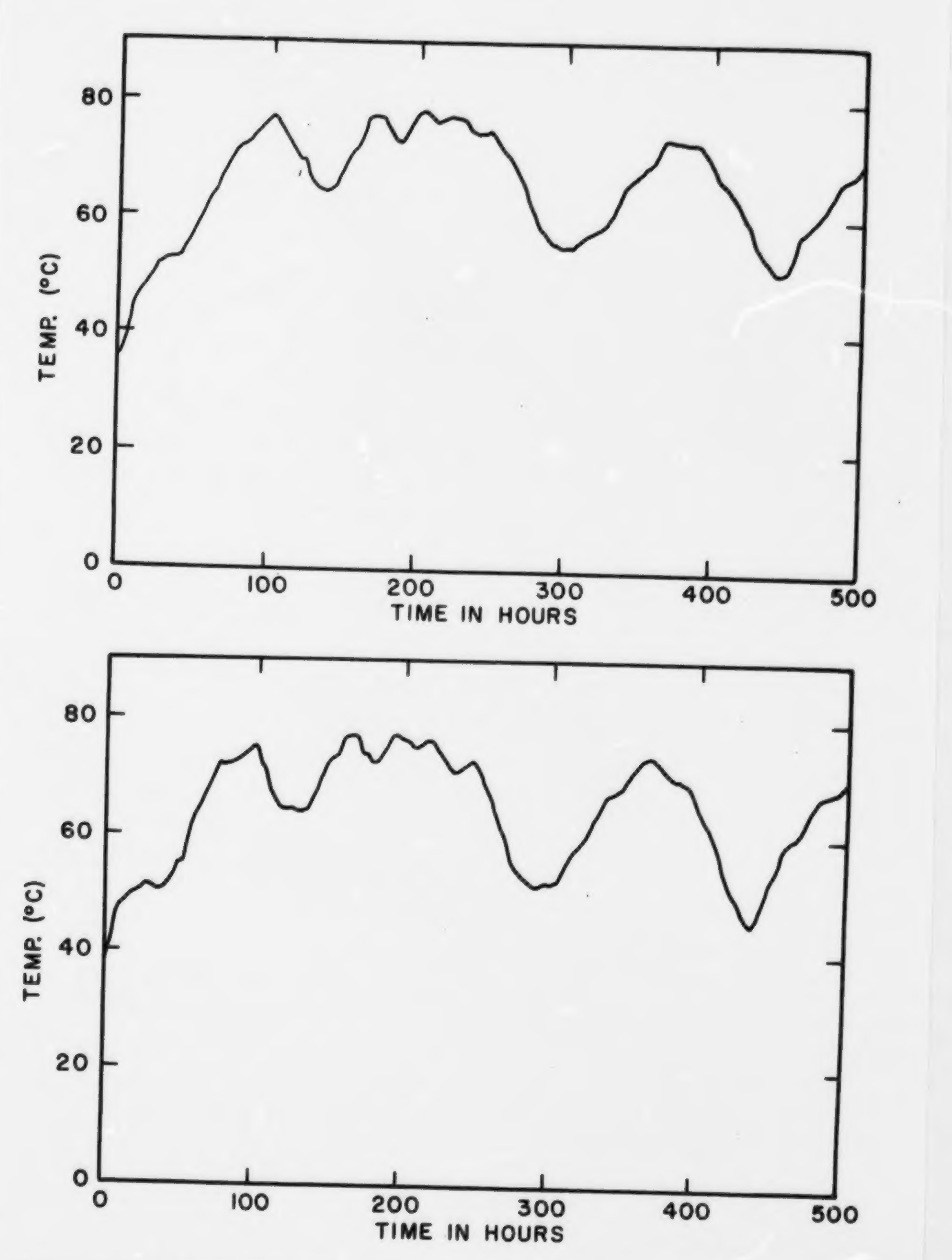


Figure 120. Pile 9B, temperature at position 11 (upper plot) and position 12 (lower plot).

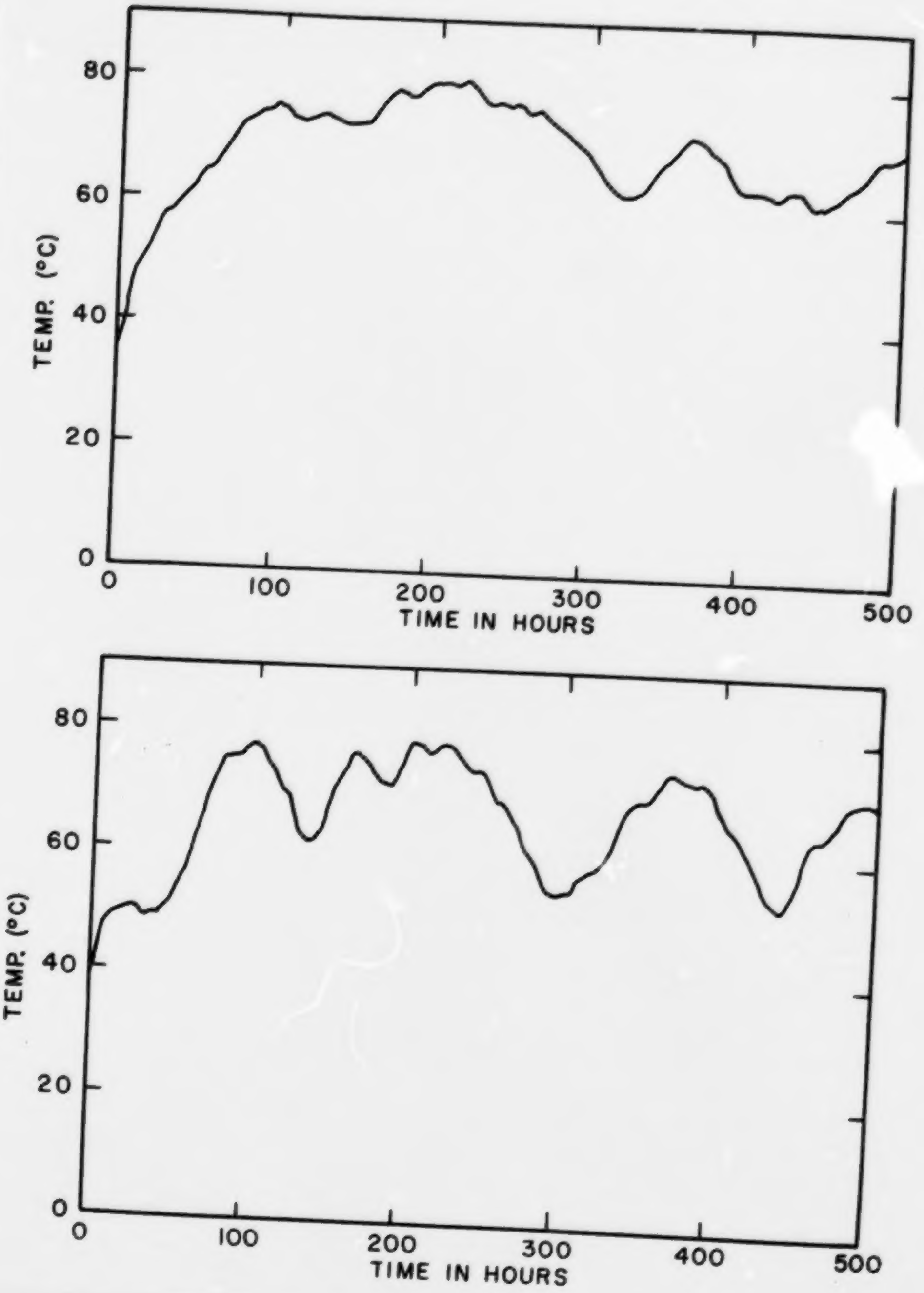


Figure 121. Pile 9B, temperature at position 13 (upper plot) and position 14 (lower plot).

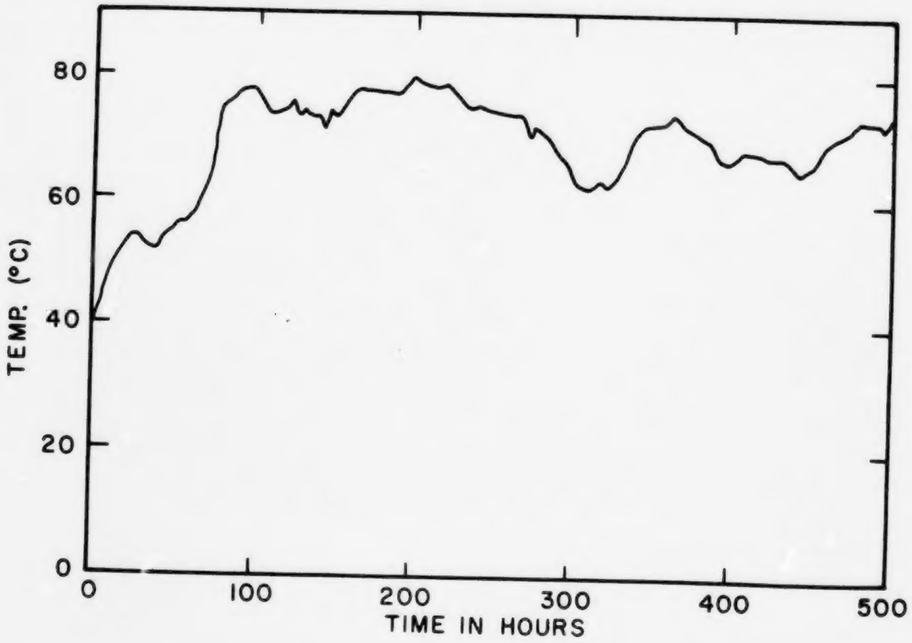


Figure 122. Pile 9B, temperature at position 15.

APPENDIX A-2

Oxygen Observations for Piles 7 and 8

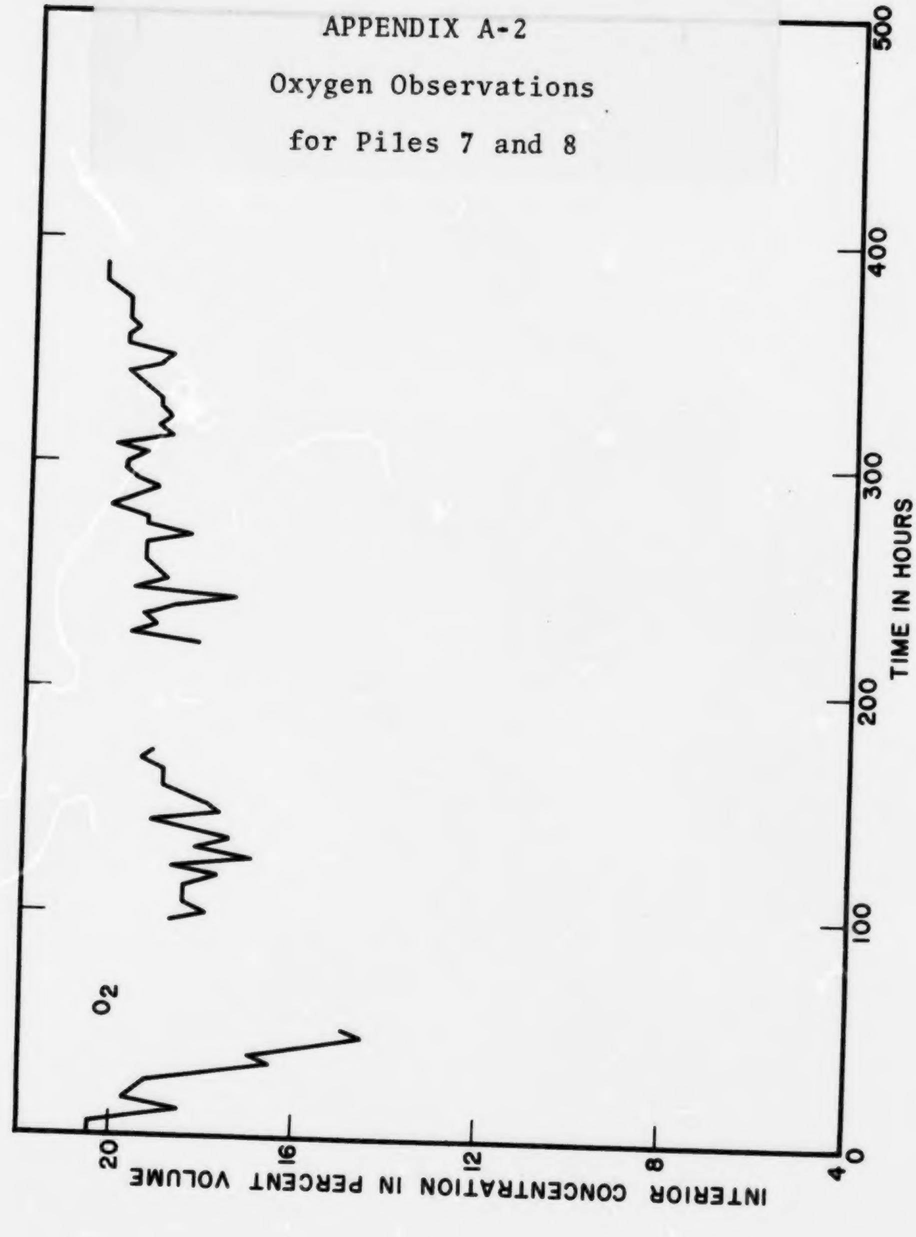


Figure 123. Pile 7, concentration of O_2. The gas sampling probe was adjacent to position 6.

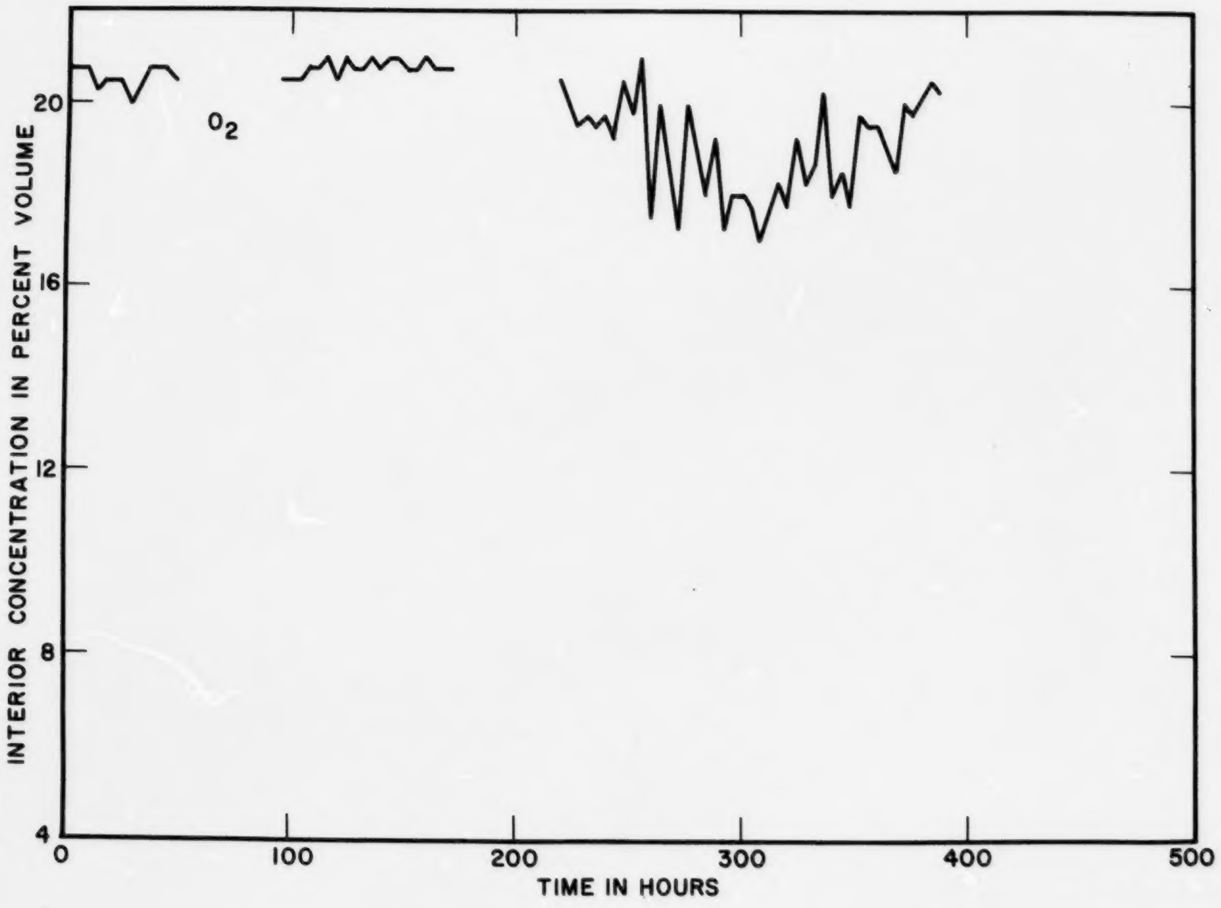


Figure 124. Pile 7, concentrations of O_2. The gas sampling probe was adjacent to position 14.

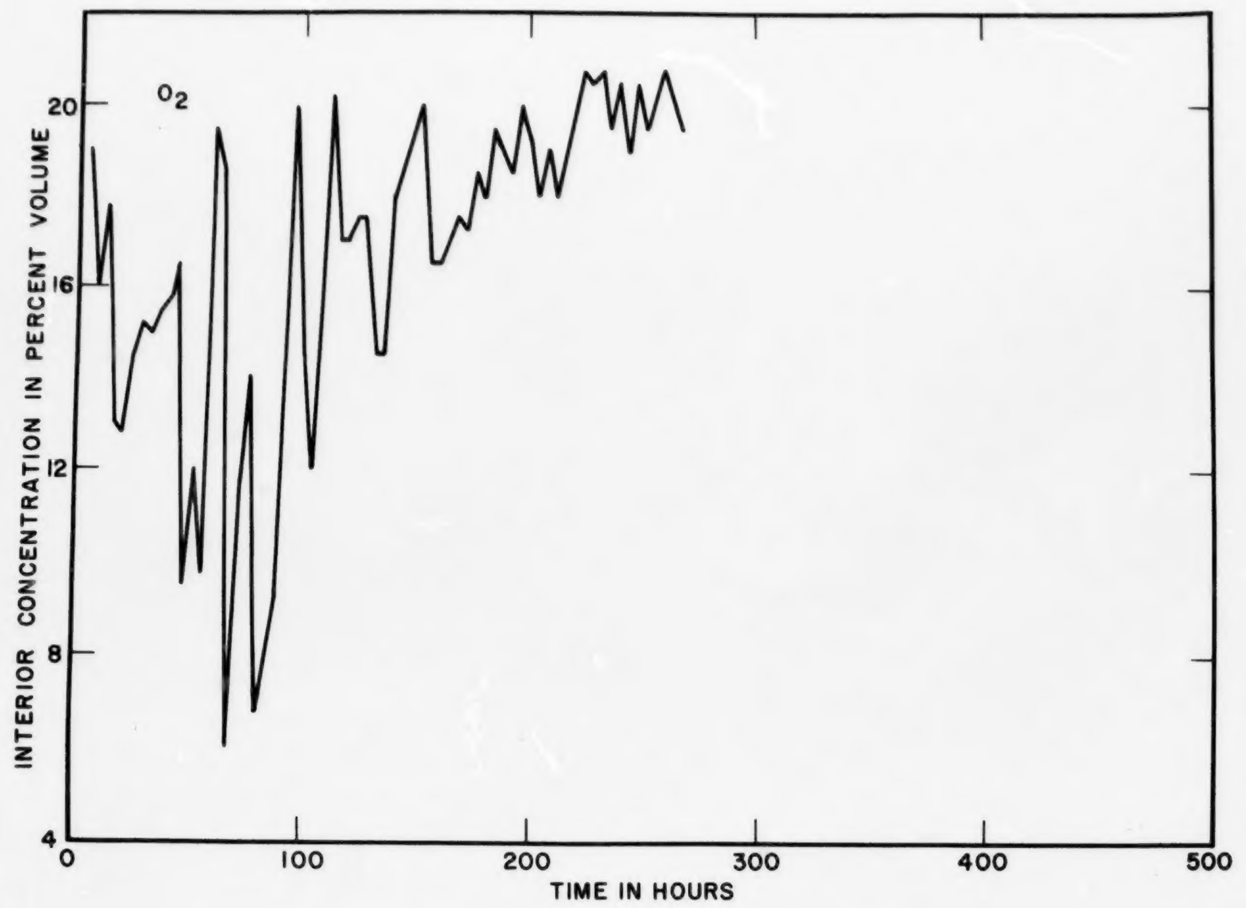


Figure 125. Pile 8, concentrations of O_2. The gas sampling probe was adjacent to position 11.

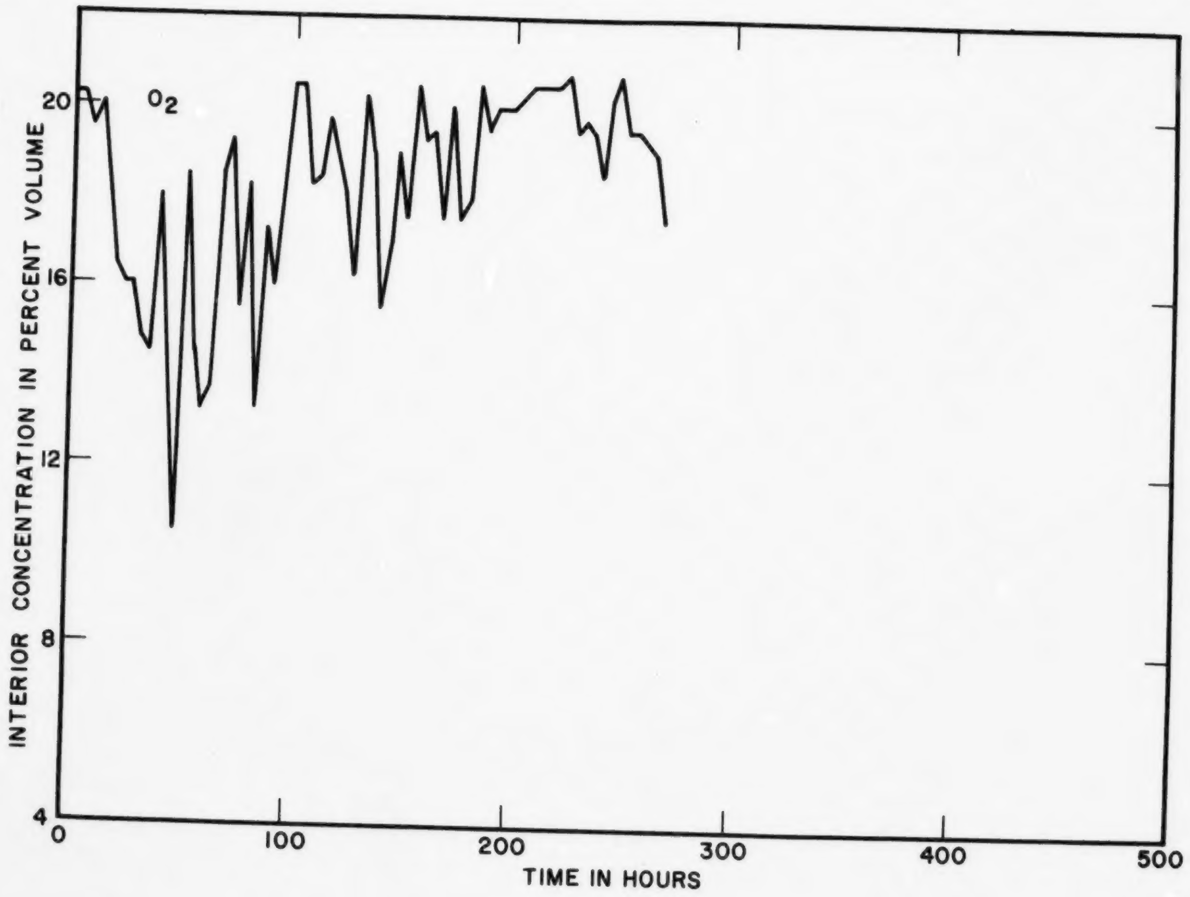


Figure 126. Pile 8, concentration of O_2. The gas sampling probe was adjacent to position 26.

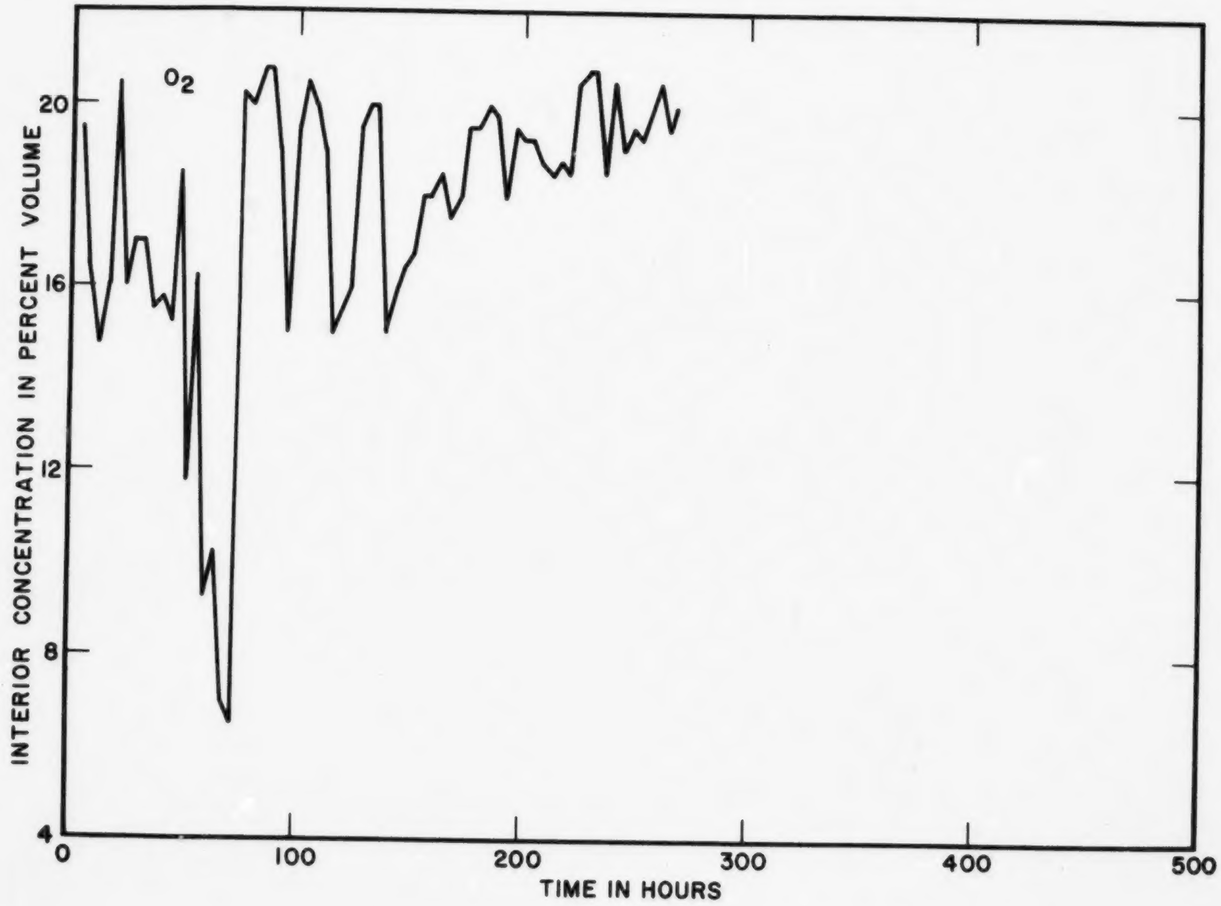


Figure 127. Pile 8, concentration of O_2. The gas sampling probe was adjacent to position 28.

APPENDIX A-3

MOISTURE CONTENT IN THE "WHOLE SAMPLE" AND THE "NON-WOODCHIP FRACTION"

When the material being composted was a mixture of sewage sludge and woodchips, two types of samples were usually processed for the determination of moisture content. These were the whole sample and the non-woodchip fraction. The non-woodchip fraction was prepared by removing the woodchips by hand. Except where not otherwise noted, the data reported in the body of the report refer to the whole sample. Both sets of data are reported in Appendix A-3, for comparative purposes.

At time-zero the moisture content of the non-woodchip fraction was higher than that of the whole sample (Figures 128, 129, 130). The difference between the moisture content of the two kinds of samples at time-zero was: pile 8, 20%; pile 9A, 5%; pile 9B, 8%. The difference disappeared in the piles which dried extensively (Rutgers strategy), but not in the pile which experienced only slight drying (Beltsville process).

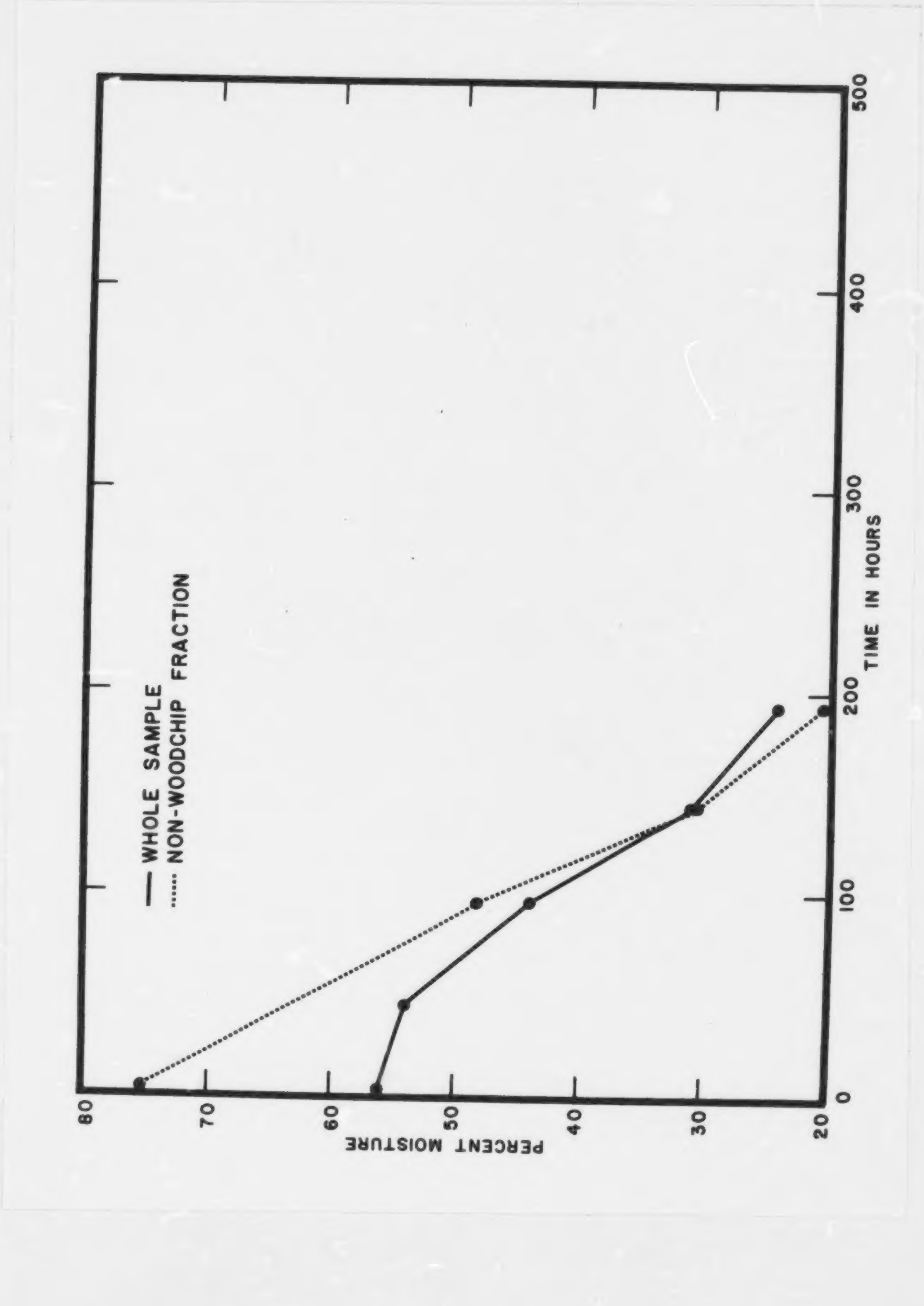


Figure 128. Pile 8, moisture content.

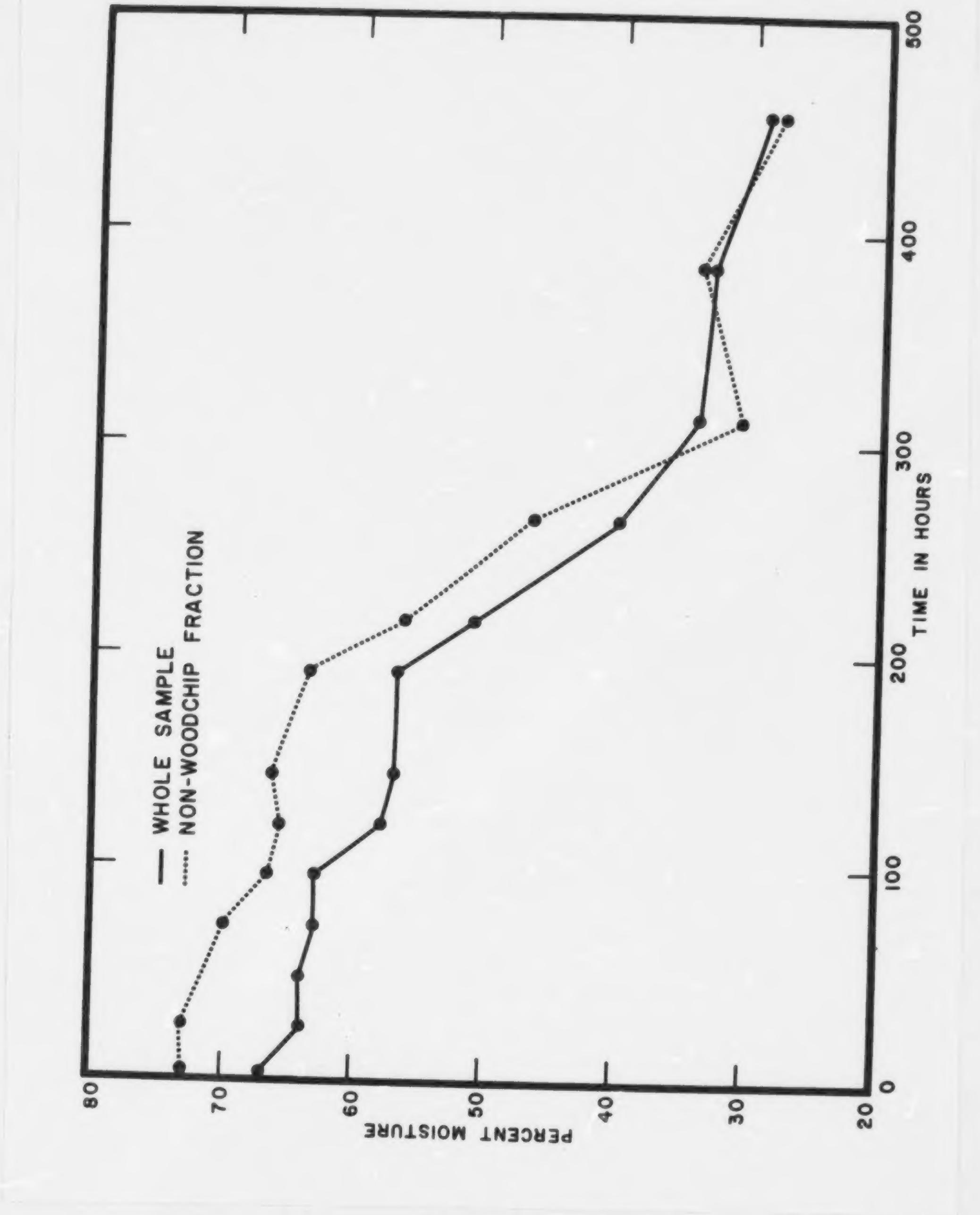


Figure 129. Pile 9A, moisture content.

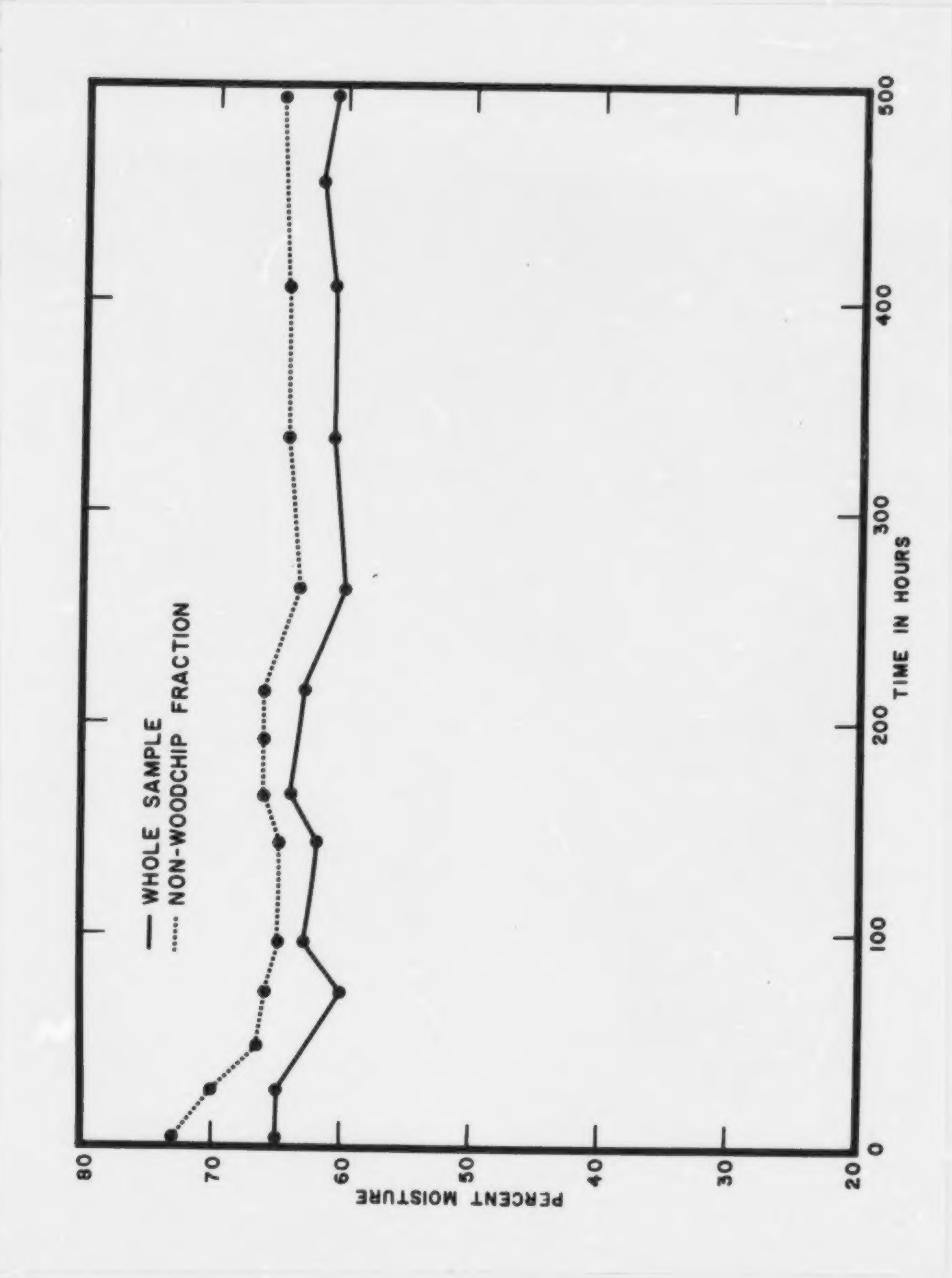


Figure 130. Pile 9B, moisture content.

APPENDIX A-4

REPRESENTATIVENESS OF PILE 9B

Since the Beltsville Process was represented herein by only one pile (9B), its representativeness was evaluated in reference to comparable data reported by other investigators. Also, the grouped Beltsville data was compared to grouped Rutgers data. The analysis is summarized in TABLE 21.

The first entry for temperature (>70°C) is based on terminal (day 21) observations (38), or on mean values (9). One of the reports (39) does not provide usable temperature data. The second entry for the Beltsville process (80°C) is based on the extensively monitored pile 9B, in which the bulk of the material peaked at 78°C to 82°C. The entry for the Rutgers process is based on the piles described in Section 3, in which the bulk of the material generally did not exceed 60°C.

The first entry concerning ventilation (O_2 level, 5-15%) is based on one pile at the end of the 21 day period. The second entry (~10%) is an "average" value, the precise meaning of which is difficult to evaluate. The third entry (12-21%) is based on pile 9B over a 21 day period, in which the gas sampling probe was centrally positioned. The entry for the Rutgers process (16-21%) is from pile 9A at a comparable position, and represents a period of 21 days. On average, the Beltsville piles were provided with 134 cfh/wet ton during the standard 21 day process period. For the Rutgers piles the blowers provided, on average, 1232 cfh/wet ton during the 12 day period of the feedback control.

The first entry concerning moisture content (7% decrease) is based on samples taken from four locations (six replicates per location) of one pile on the terminal day of standard processing (38). Reference 9 does not include suitable moisture content data. The second entry (14% decrease) represents 114 piles on the terminal day (processing was usually for 21 days). The third entry (4% decrease) is the final value of the series representing pile 9B. The fourth entry (34% decrease) represents the mean final value of the indicated Rutgers piles.

TABLE 21. COMPARISON OF FIELD DATA FOR RUTGERS AND BELTSVILLE PROCESSES.

Process	Peak temperature representing the bulk of the pile (°C)	Ventilation requirement to maintain an oxygenated condition		Decrease in moisture content (%)*	Process time (days)	Reference or pile
		O_2 level (%)	cfh/ton†			
Beltsville	>70	5-15	60-133	7	21	9, 38-39
Beltsville	--	10	212‡	14	21	39
Beltsville	80	12-21	132	4	21	Pile 9B
Rutgers	60	16-21	1232§	34	12	Piles 4A#, 7; 8, 9A

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* Woodchips included in the sample, except that for pile 4A the sample was sieved before the determination.

† Mean delivery per ton (wet wt) of the initial sludge-woodchip mixture. To convert from cfh to m^3/s, multiply x 7.87 x 10^{-6}; to convert from ton to tonne (metric), multiply x 0.908.

‡ The published value is 123 cfh/yd^3. This was converted to the common means of expression by assuming that 1.74 yd^3 weighs 1.0 ton.

§ Peak demand ~ 4800 cfh/ton

# See Section 4.

APPENDIX A-5

FORCES DRIVING VAPORIZATION: METABOLICALLY GENERATED HEAT, AND UNSATURATION OF INLET AIR

The experimentally derived value of 4.5% was calculated as the H_2O removed per unit volume air from a metabolically inert pile of cured compost x 100/H_2O removed per unit volume air from an actively composting pile. (See Section 8 for observations on a pile of well-cured compost -- pile 12.) The calculation leading to the theoretical values (1.8% to 5.0%) assumes that ambient inlet air at 20°C and 50% relative humidity (RH) is introduced into two physically identical piles: one an actively composting pile; the other a metabolically inert pile. Upon exiting from the composting pile the air is at 60°C and 100% RH, hence water removal amounts to 0.145 kg/kg dry air (46). For the metabolically inert pile two extreme cases are developed. The first assumes that the air experiences the maximum theoretical temperature decrease with passage through the pile. Upon exiting the air is at 13.3°C and 100% RH, hence water removal is 0.0026 kg/kg dry air. The second case assumes no temperature decrease, giving exit air at 20°C and 100% RH and water removal of 0.0072 kg/kg dry air. Thus, in this calculation non-biological air drying caused by unsaturation of the air accounts for only 1.8% to 5.0% of the water removal from the composting pile. The remainder is attributable to microbial heat generation.

APPENDIX A-6

RELATIVE SENSITIVITY OF THE MOISTURE CONTENT AND VOLATILE SOLIDS TESTS

Consider the relationship between the decrements of organic matter and water on a mass basis. Assuming a release of 6000 cal from the microbial oxidation of 1 g organic matter to CO_2 and H_2O, and with the heat of vaporization of water at 20°C (the assumed temperature of the inlet air and starting material) equal to 586 cal/g, 10.2 g water could be vaporized per g volatile matter decomposed. A small part of the water loss is made up through metabolic water production (ca., 0.8 g). Also, 4% (at 80°C exit temperature) to 14% (at 50°C) of the heat removal is through dry air convection, and another 2% (at 50°C) to 4% (at 80°C) through raising the temperature of the vaporized water. Hence, the mass of water removed provides an indication of organic matter decomposition that is 7.8 (at 50°C) to 8.6 (at 80°C)-fold more sensitive than the mass of volatile solids decomposed.

The mass of water removed is rarely known, however, whereas the % moisture content is easily determined. Under realistic conditions, the ratio change in % moisture/change in % volatile solids exceeds unity at the outset of composting, and widens progressively due to the different relative changes in the remaining masses of water and volatile solids. The widening of the ratio is mainly a function of the initial moisture content and the initial volatile solids content, hence no further generalization regarding its numerical value is possible. In the case of an initial moisture content of 75% (wet weight basis) and volatile solids content of 75% (dry weight basis), as the moisture content traverses the 30% level the cumulative ratio is 3.5. In association with a decrease in moisture content from 31% to 30%, the ratio is 9.8.

APPENDIX B

ADVANTAGES OF FUEL PRODUCTION THROUGH COMPOSTING VS. DIRECT COMBUSTION SEWAGE SLUDGE CAKE

General Advantages

- The residue of the composting process is metabolically inert, and therefore relatively easy to handle, stockpile, and transport.
- The process residue is dry and granular, or can be pulverized to granulate it, making it relatively easy to feed into the combustion chamber.
- Separation of the drying and combustion functions improves overall system reliability, in that a breakdown of the combustion system does not interfere with the sludge treatment (≡fuel preparation).

Thermodynamic Advantages

Separation of the drying and combustion functions decreases the amount of energy spent in the vaporization of water. This stems from a comparison of biological drying (composting) at 140°F versus direct combustion at 1500°F. Note that for every pound of water vaporized at 140°F (via biological drying), approximately 680 BTU's are saved compared to combustion at 1500°F.* This reflects the approximately 0.5 BTU's/lb/°F required to raise the temperature of water vapor over this range.

A further advantage, not as easily quantitated in the general case, is that less total air is required for the combustion. For every pound of air not required, approximately 370 BTU's are saved, reflecting the 0.26 BTU/lb/°F specific heat of air over this range.

Energy must be expended in biological drying (composting), of course and this decreases somewhat the thermodynamic advantage. No exact accounting is readily accessible, but it is evident that biological drying is advantageous compared to air drying (see TABLE 12.)

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*Steam: Its Generation and Use, 37th Edition, 1963. The Babcock & Wilcox Company, New York.

APPENDIX C

Temperature Observations for Piles 11A, 11B, and 11C

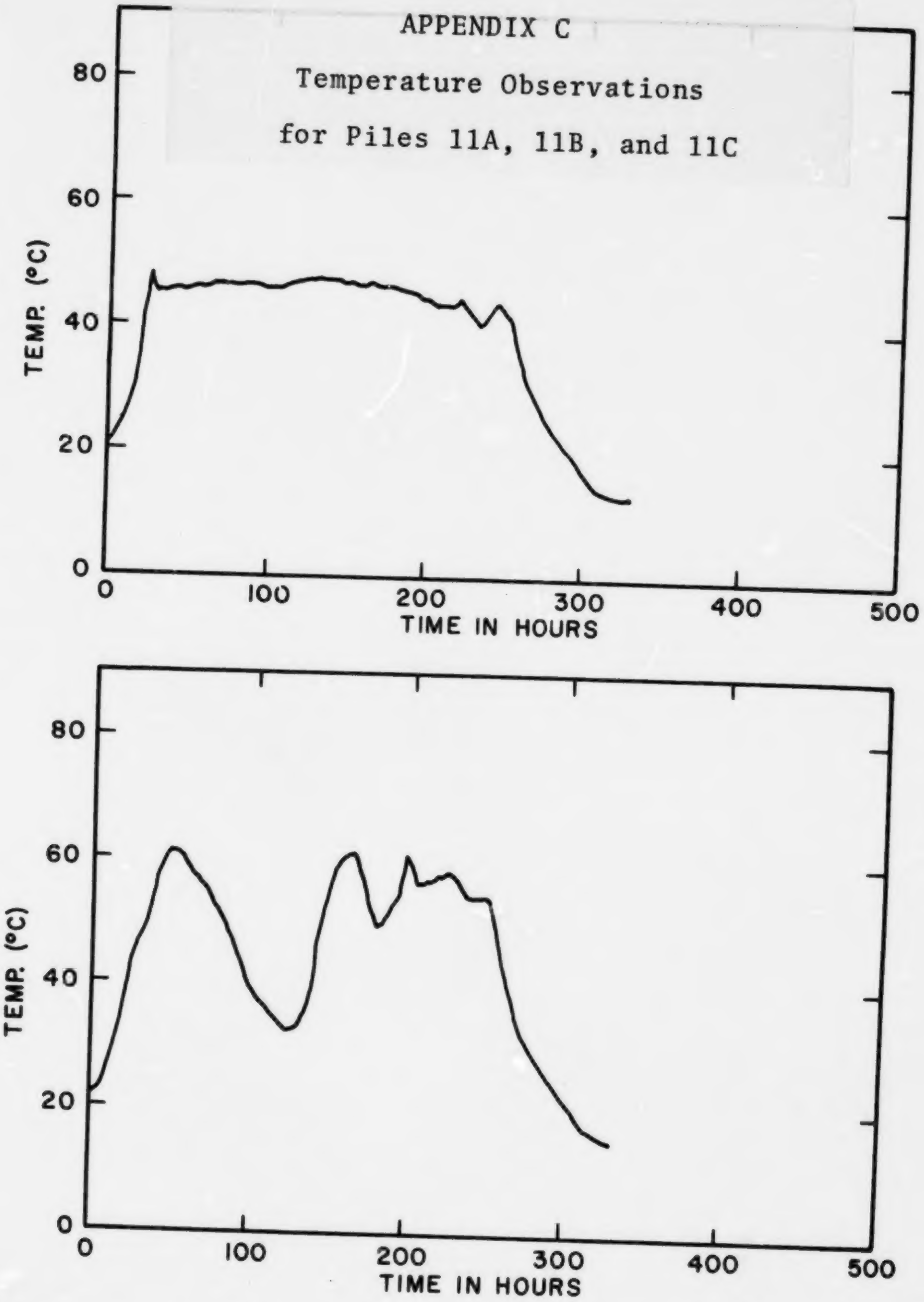


Figure 131. Pile 11A, temperature at position 1 (upper plot) and position 2 (lower plot).

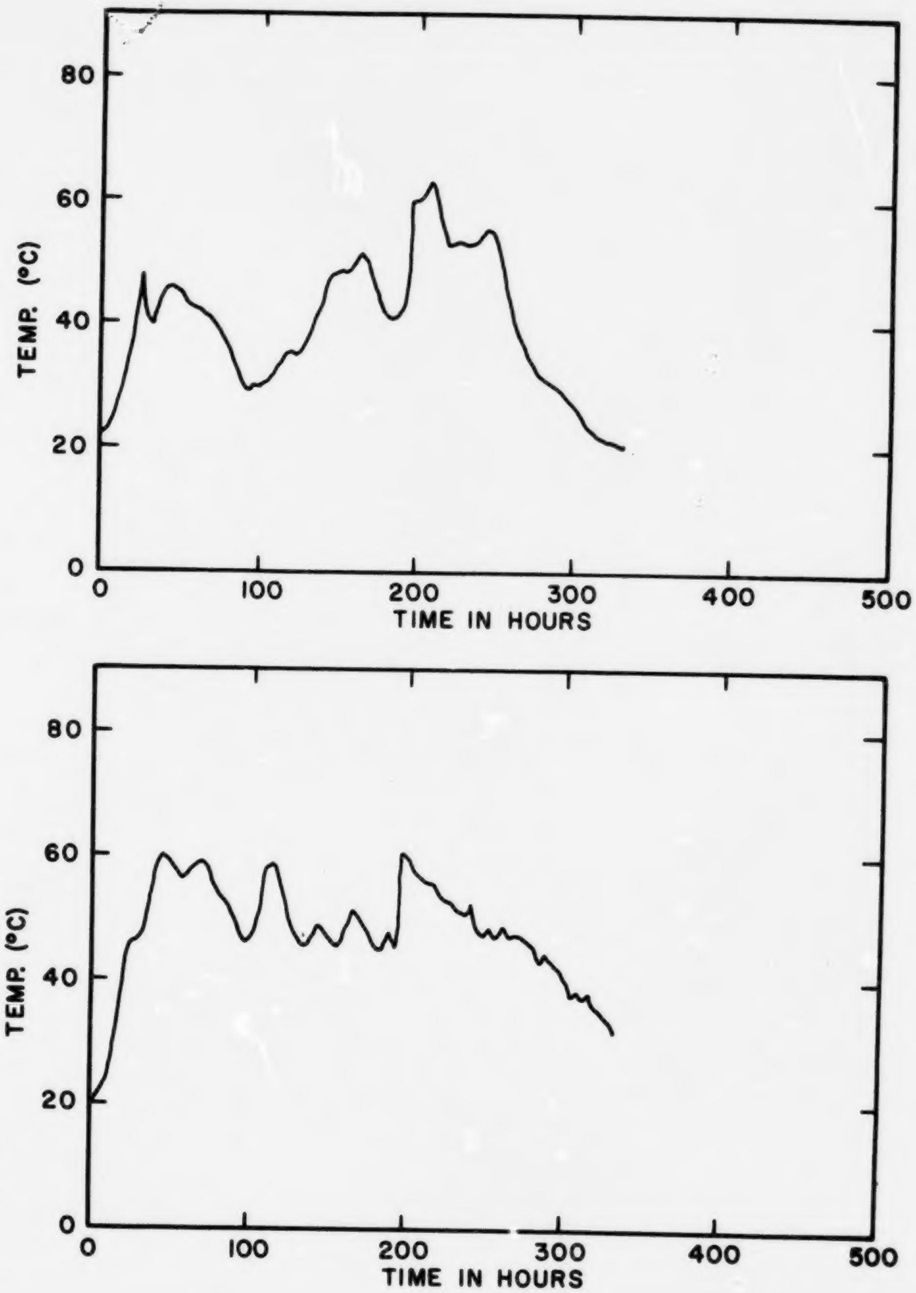


Figure 132. Pile 11A, temperature at position 3 (upper plot) and position 4 (lower plot).

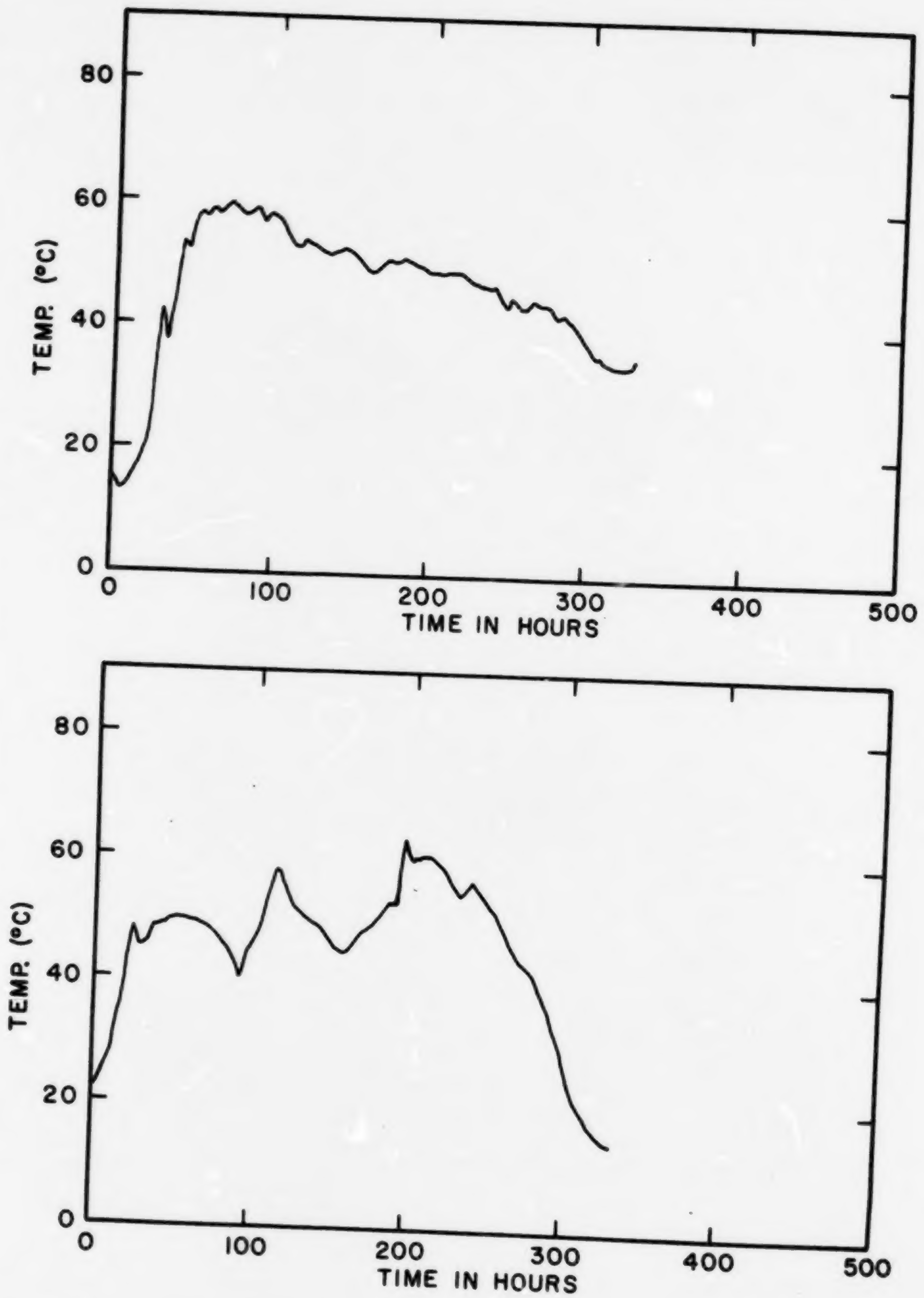


Figure 133. Pile 11A, temperature at position 5 (upper plot) and position 6 (lower plot).

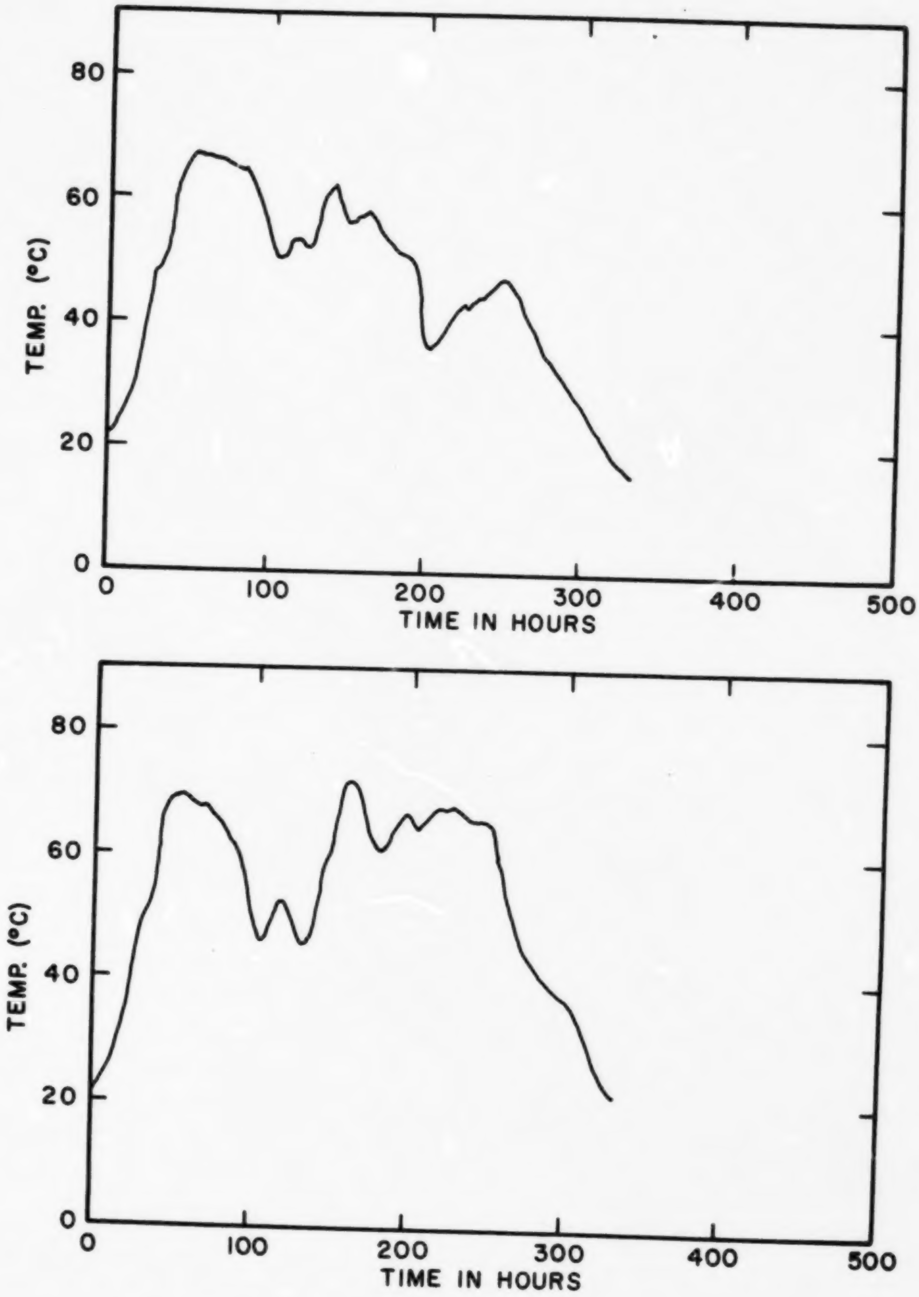


Figure 134. Pile 11A, temperature at position 7 (upper plot) and position 8 (lower plot).

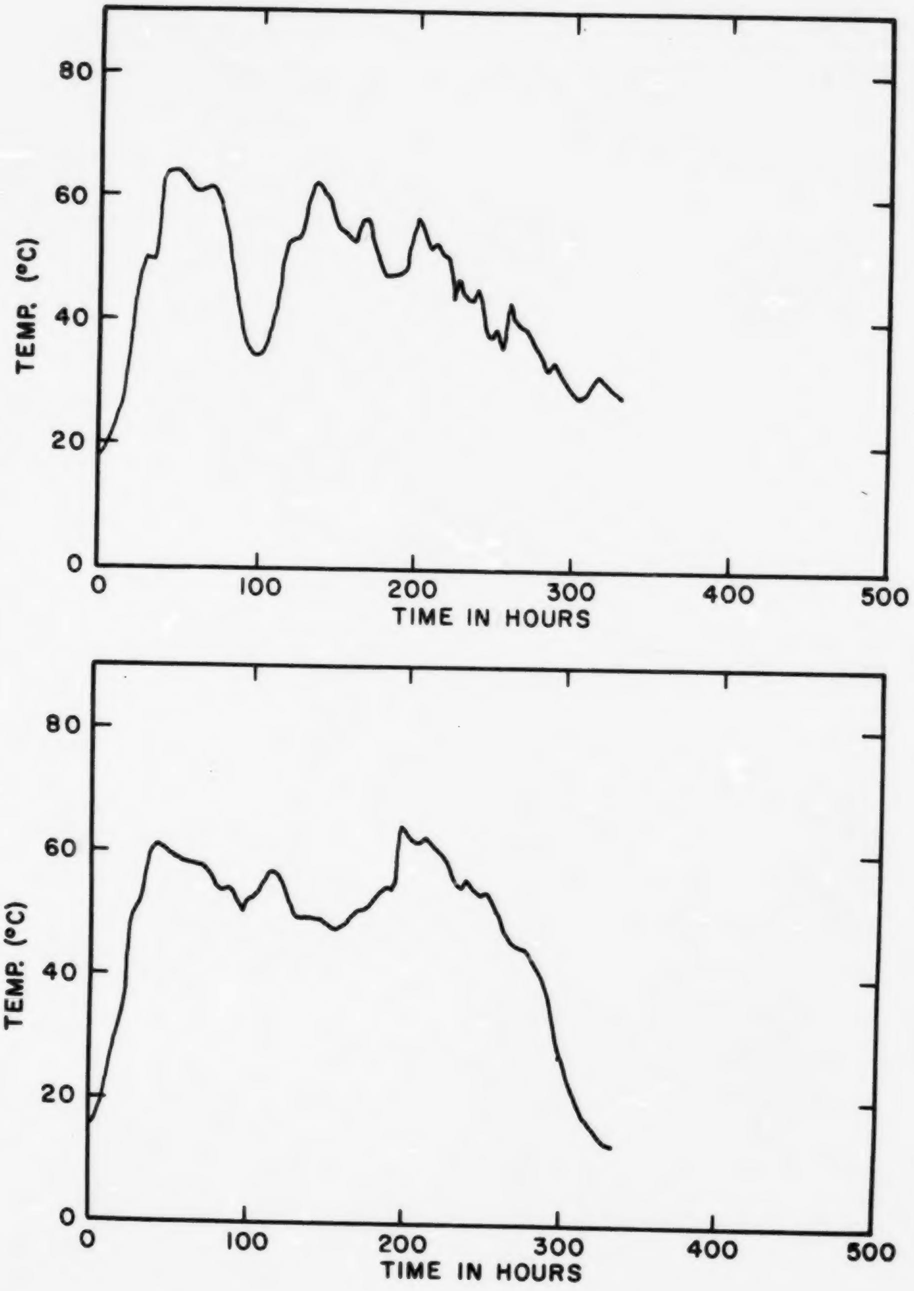


Figure 135. Pile 11A, temperature at position 9 (upper plot) and position 10 (lower plot).

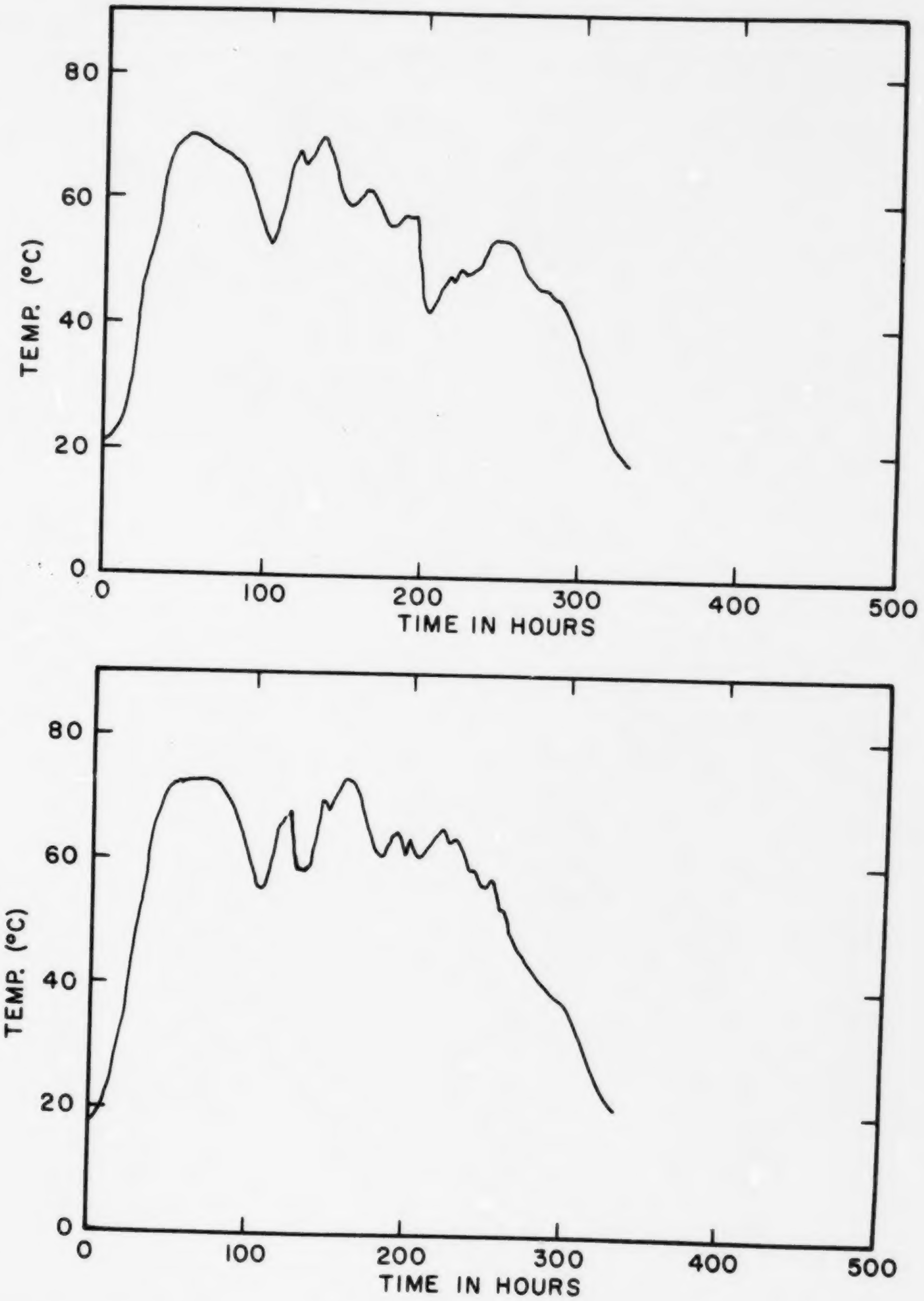


Figure 136. Pile 11A, temperature at position 11 (upper plot) and position 12 (lower plot).

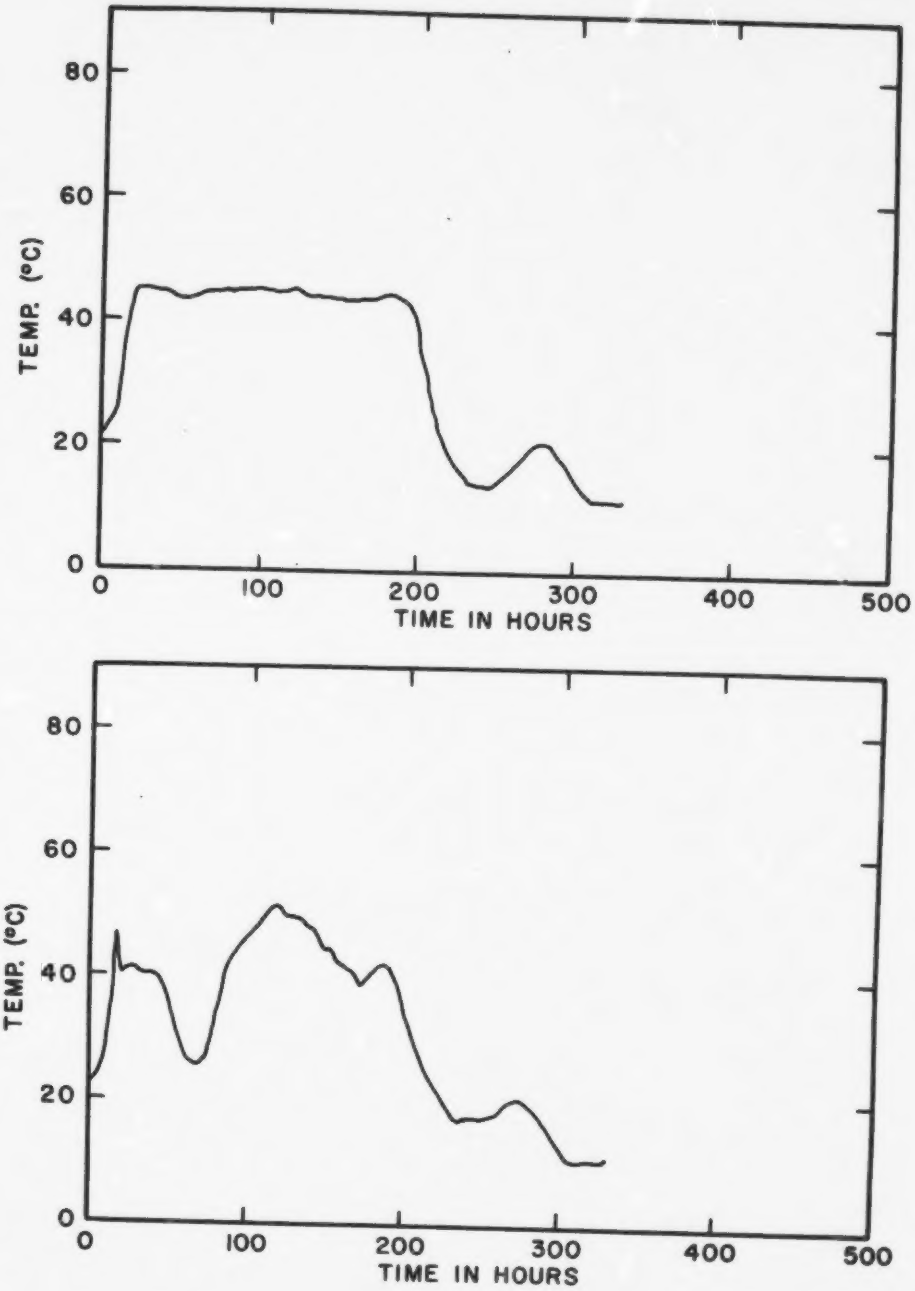


Figure 137. Pile 11B, temperature at position 1 (upper plot) and position 2 (lower plot).

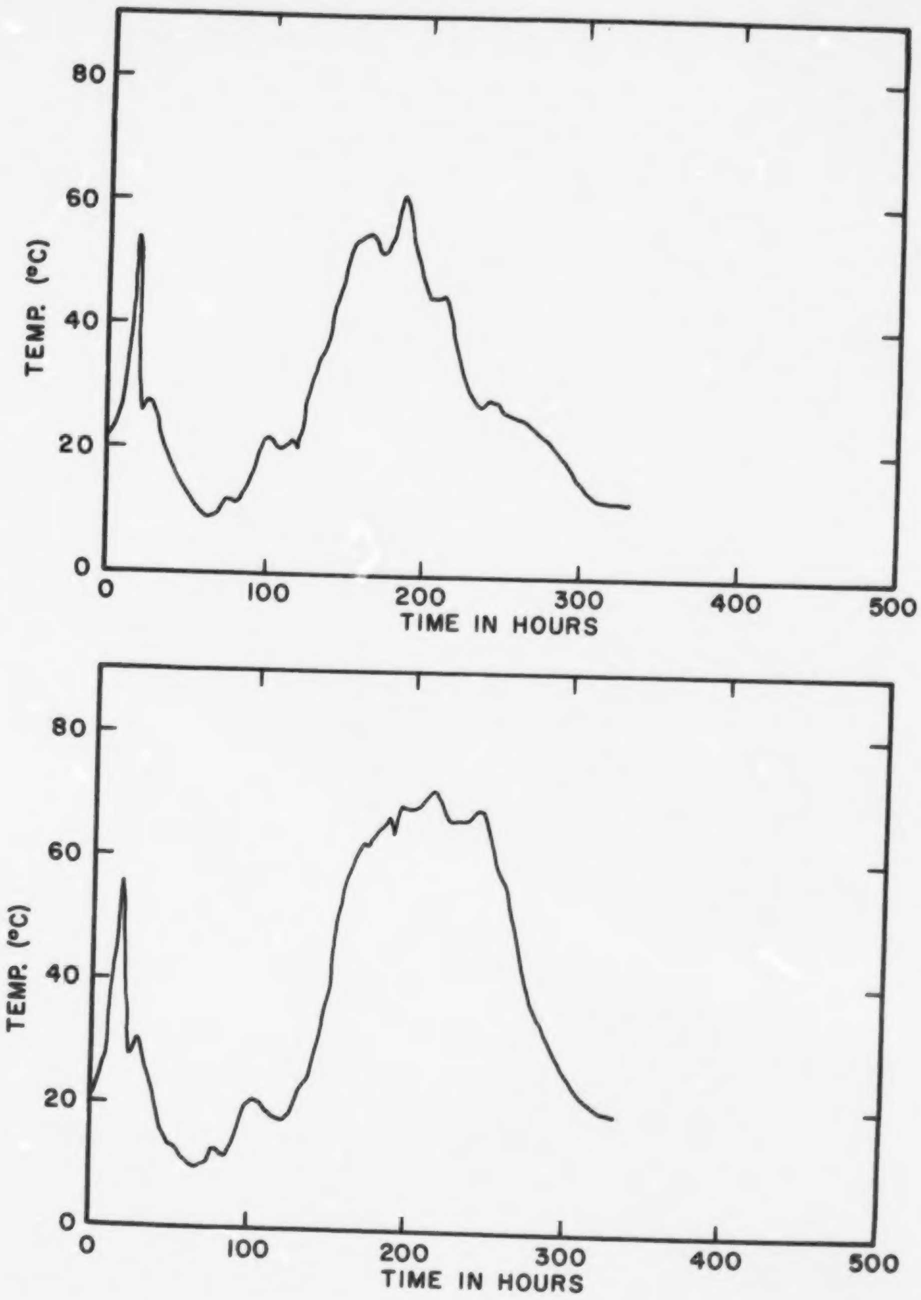


Figure 138. Pile 11B, temperature at position 3 (upper plot) and position 4 (lower plot).

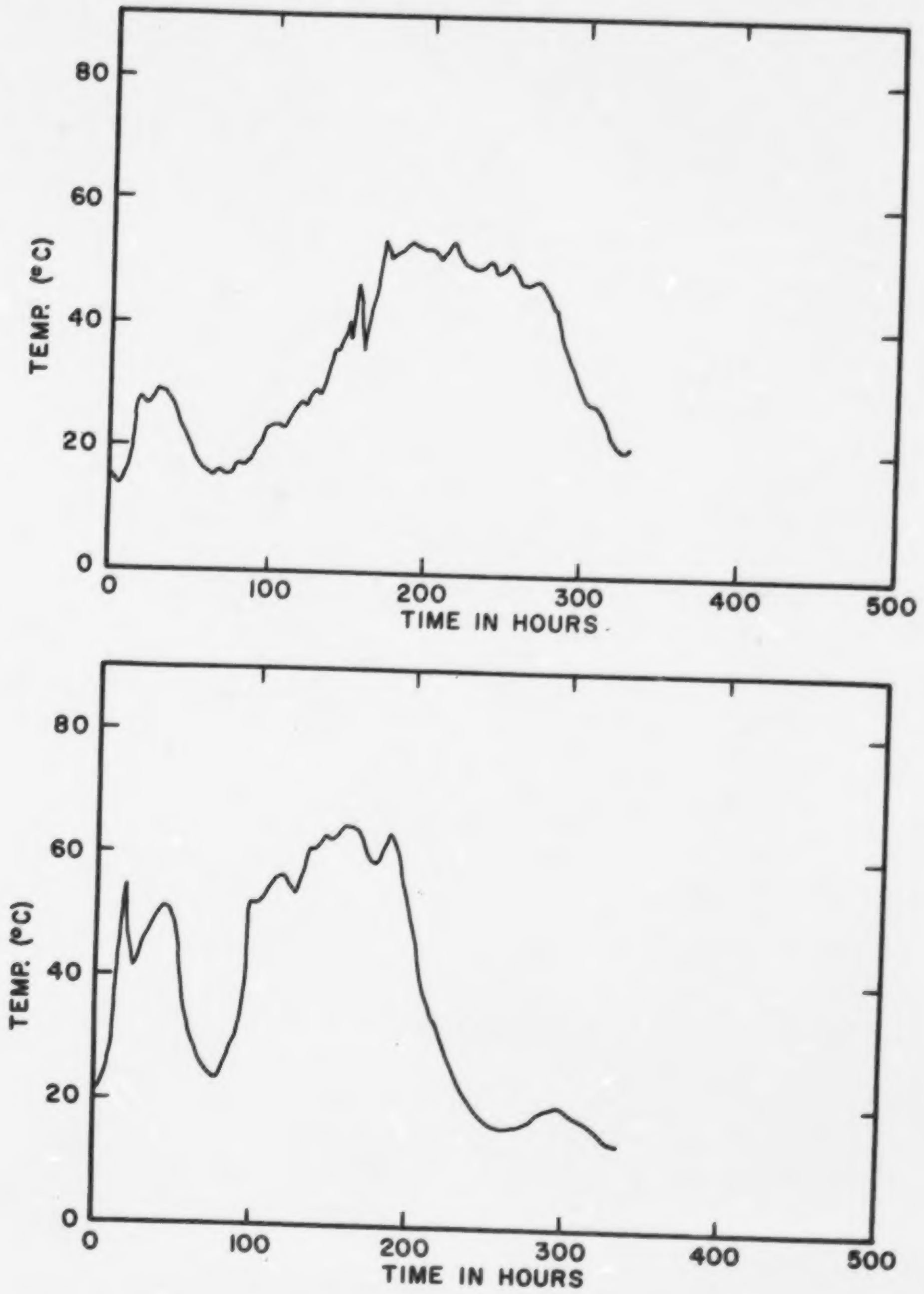


Figure 139. Pile 11B, temperature at position 5 (upper plot) and position 6 (lower plot).

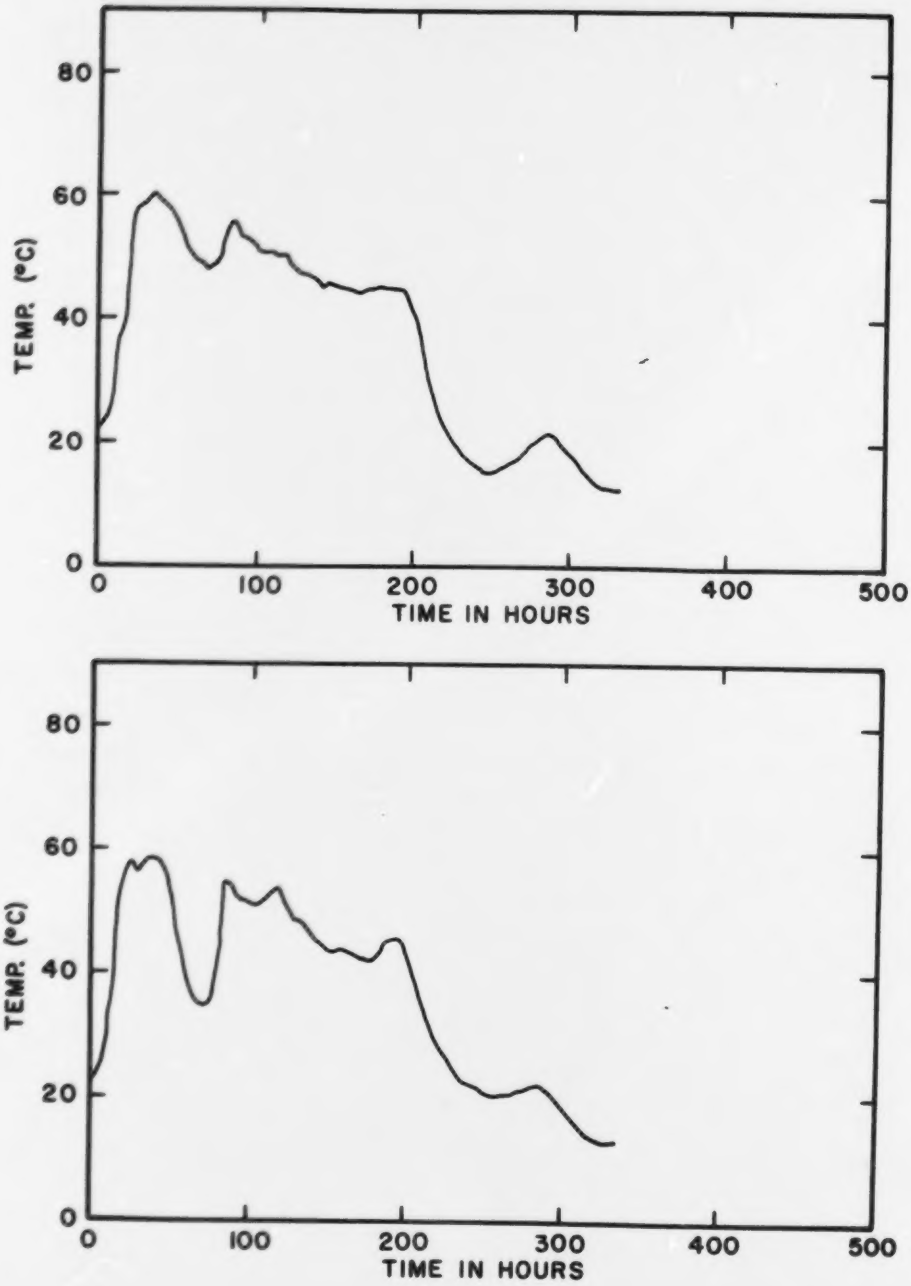


Figure 140. Pile 11B, temperature at position 7 (upper plot) and position 8 (lower plot).

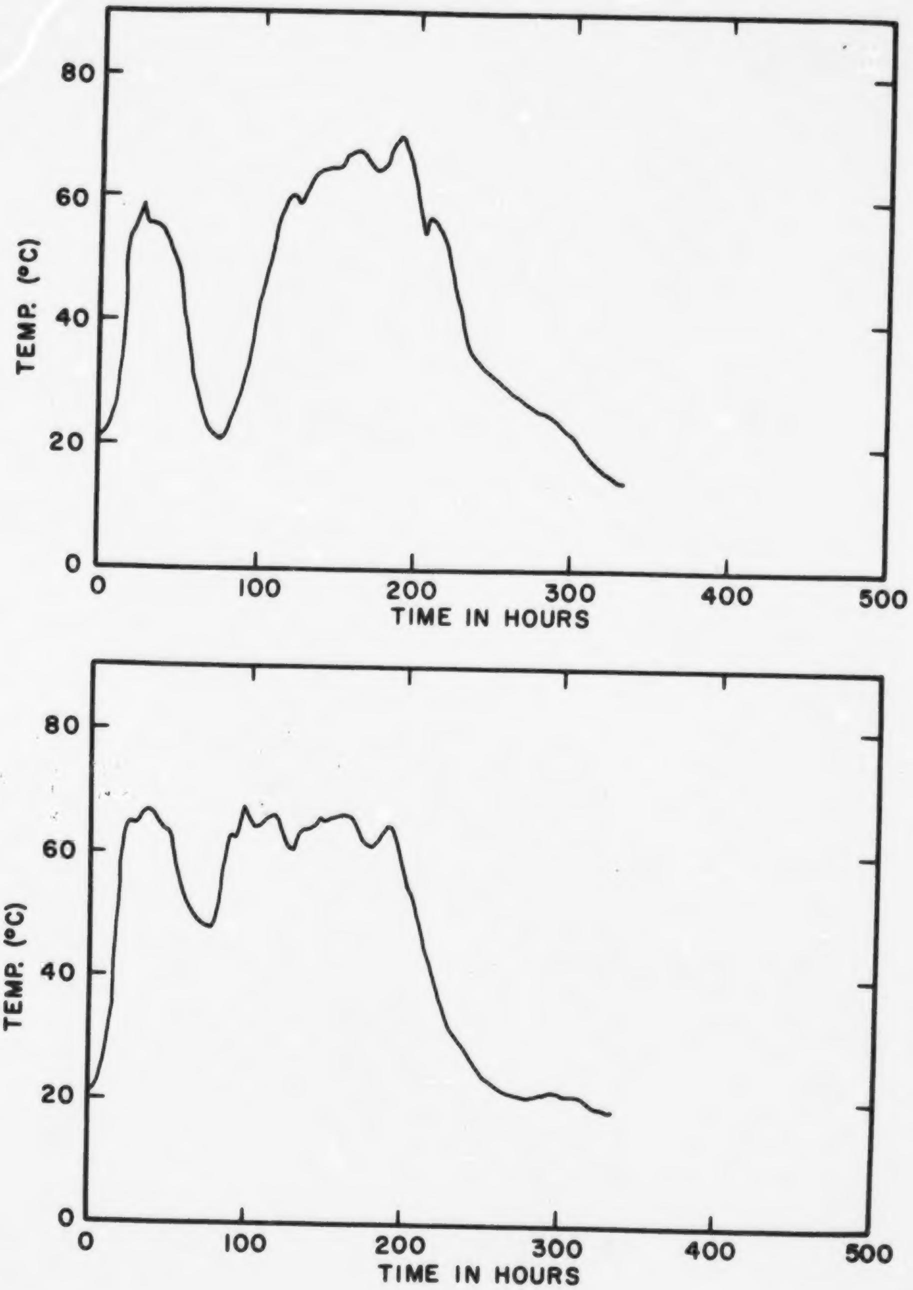


Figure 141. Pile 11B, temperature at position 9 (upper plot) and position 10 (lower plot).

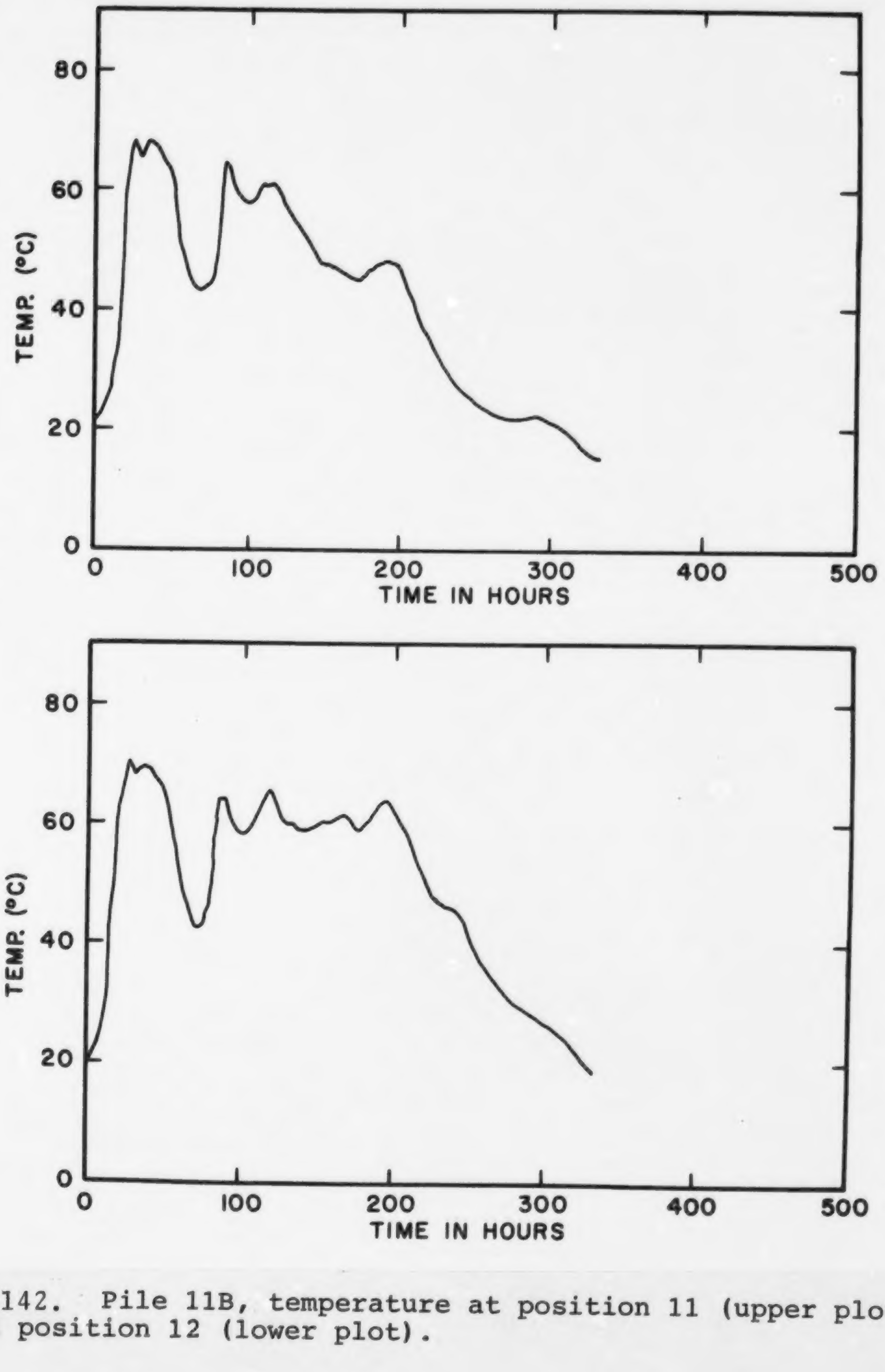


Figure 142. Pile 11B, temperature at position 11 (upper plot) and position 12 (lower plot).

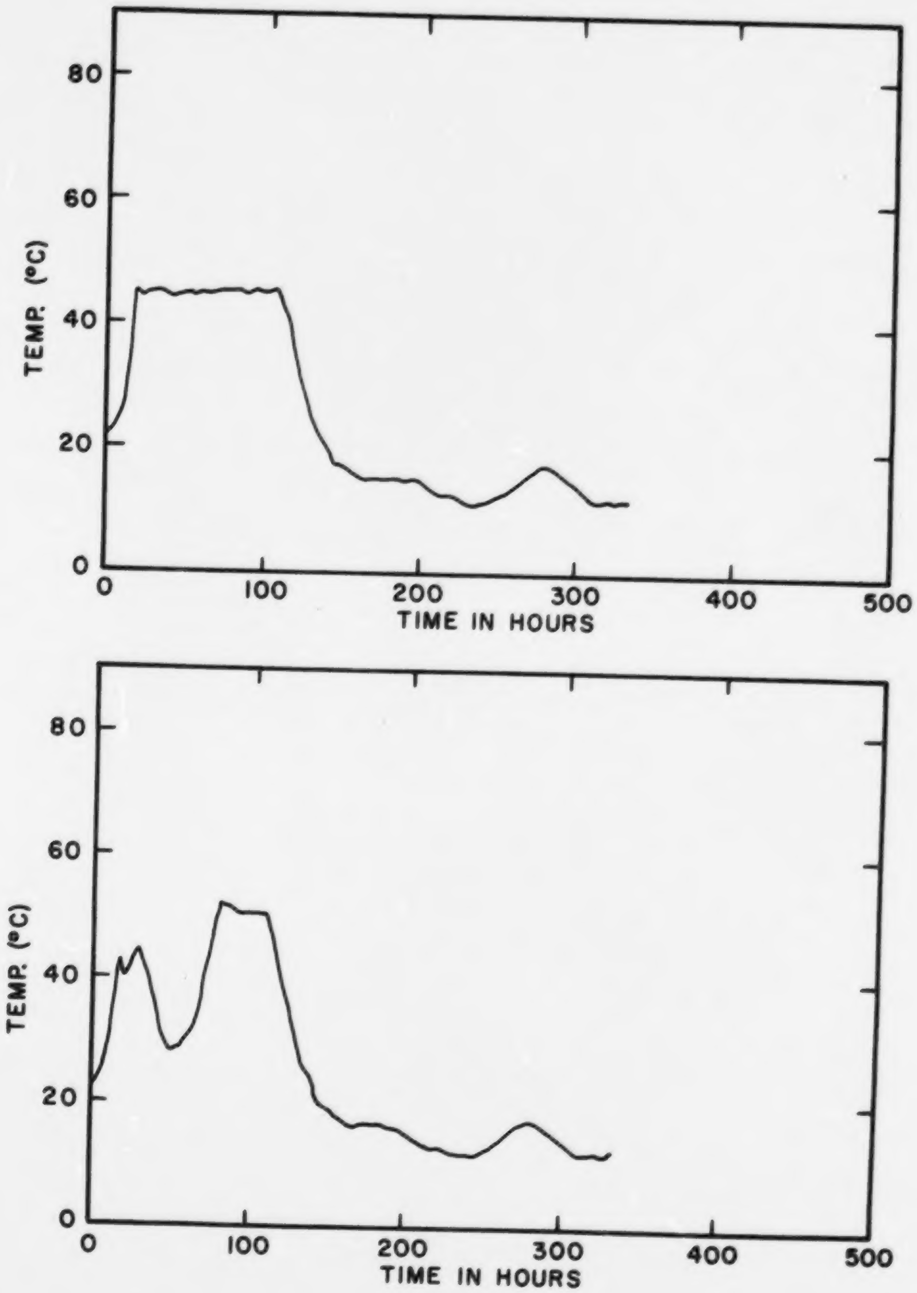
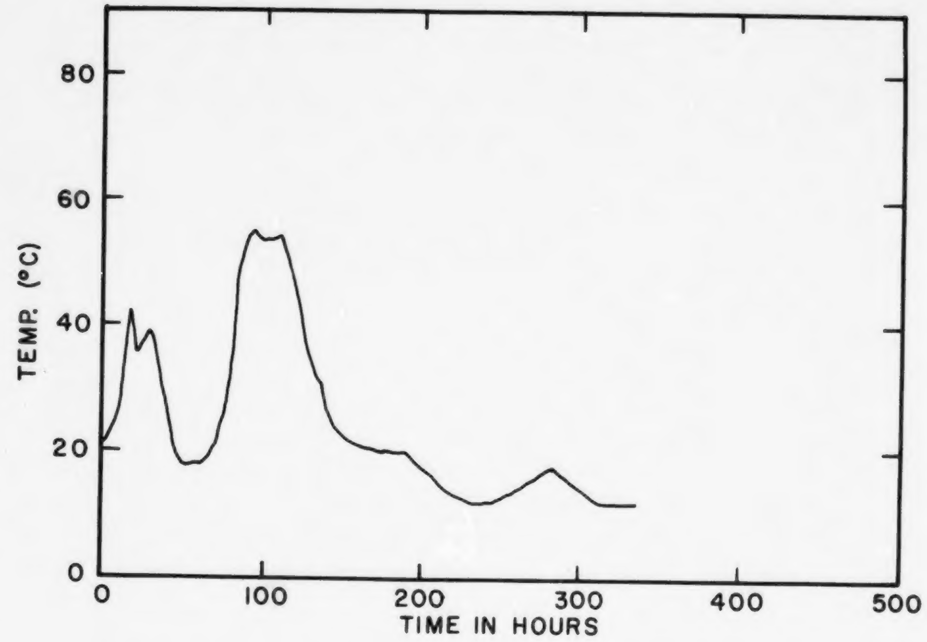


Figure 143. Pile 11C, temperature at position 1 (upper plot) and position 2 (lower plot).



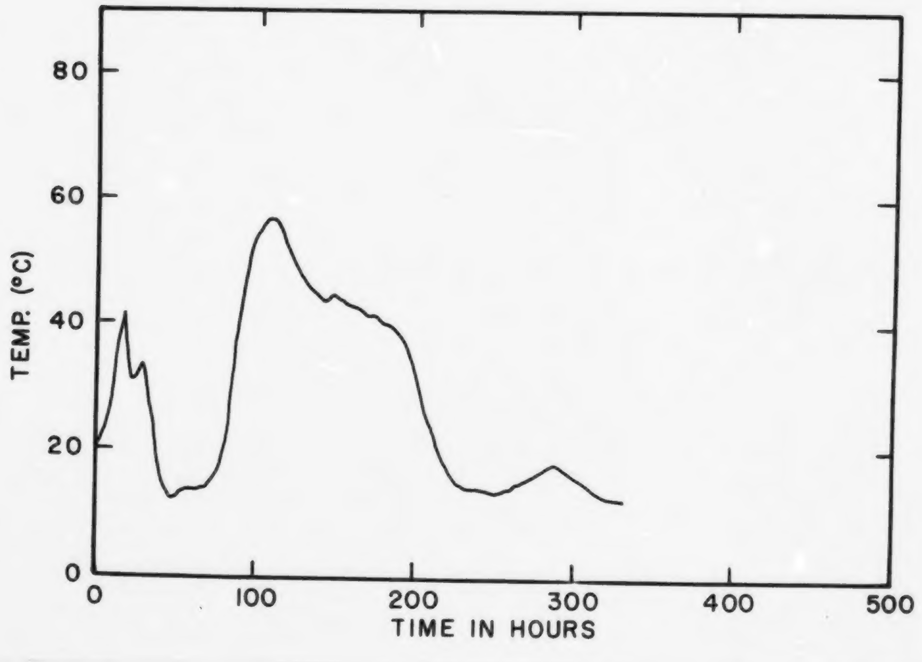


Figure 144. Pile 11C, temperature at position 3 (upper plot) and position 4 (lower plot).

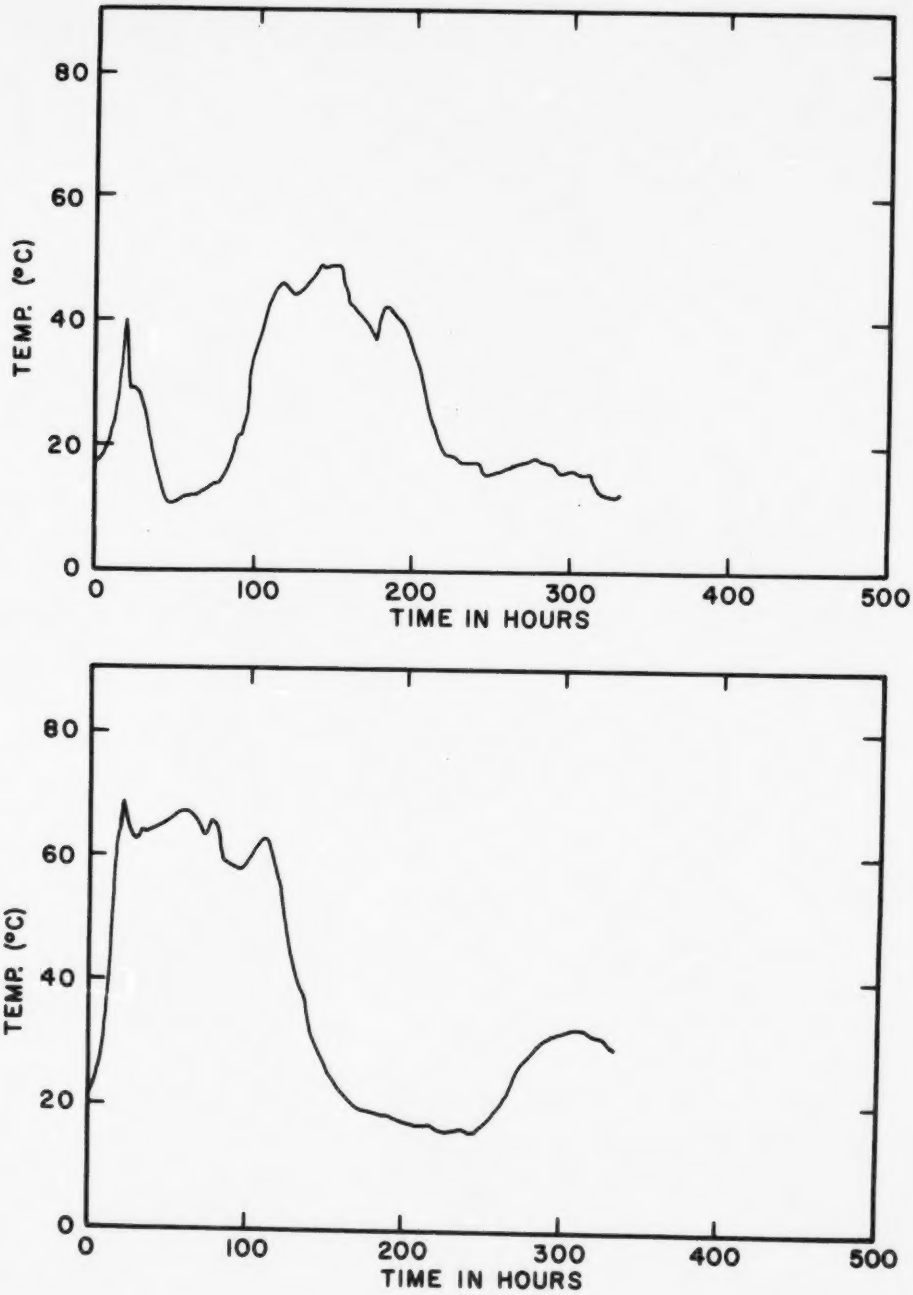


Figure 145. Pile 11C, temperature at position 5 (upper plot) and position 6 (lower plot).

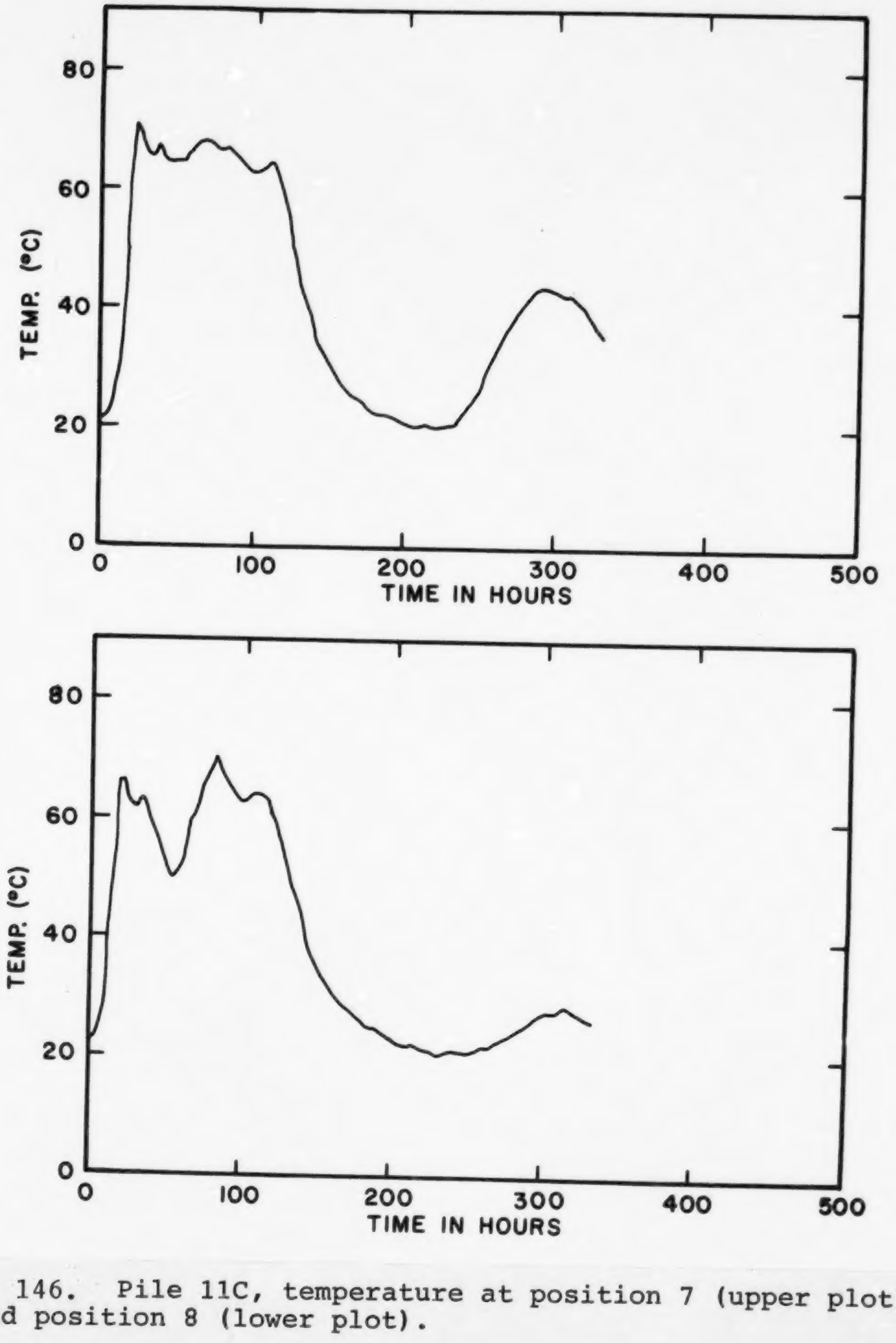


Figure 146. Pile 11C, temperature at position 7 (upper plot) and position 8 (lower plot).

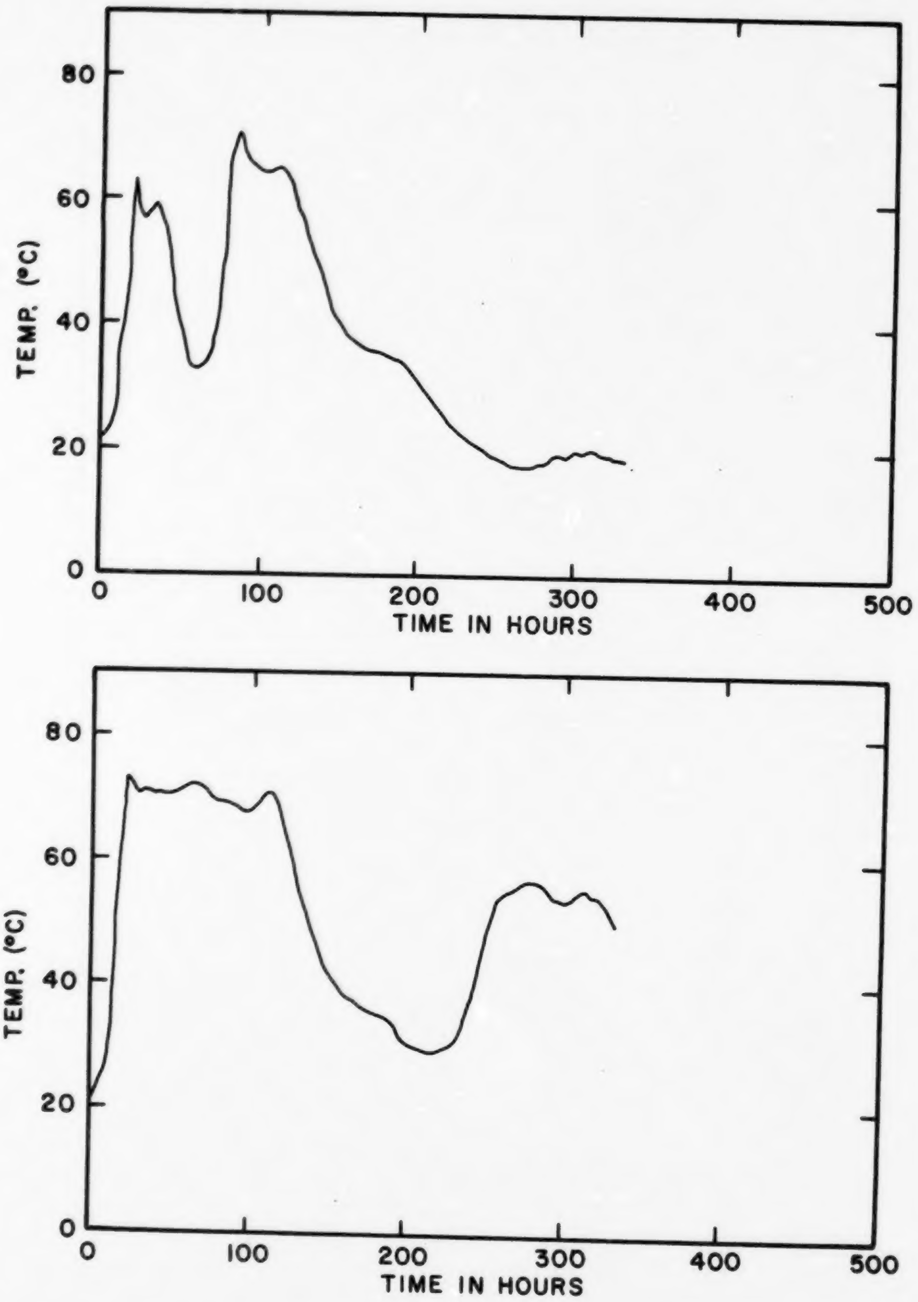


Figure 147. Pile 11C, temperature at position 9 (upper plot) and position 10 (lower plot).

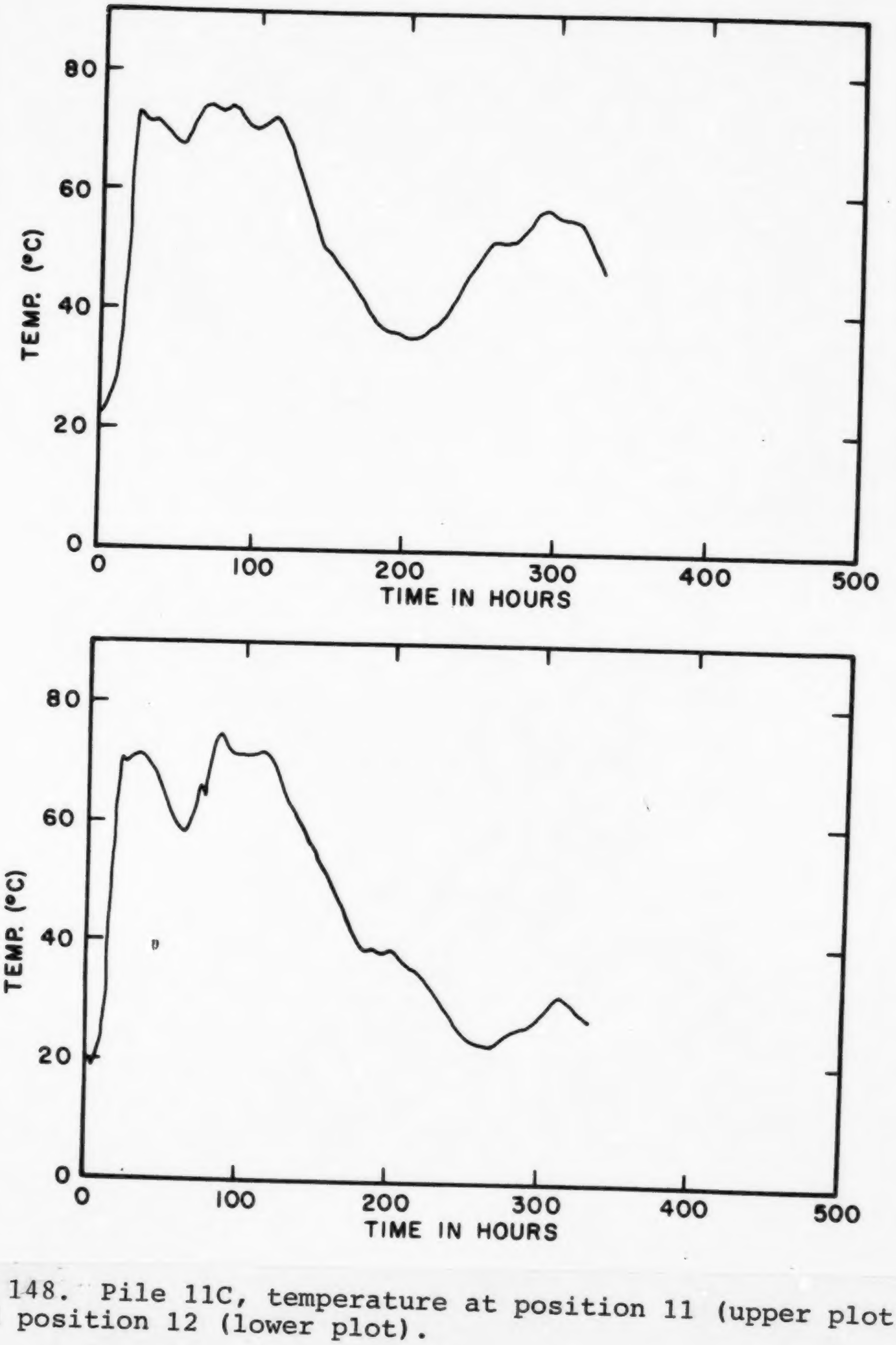


Figure 148. Pile 11C, temperature at position 11 (upper plot) and position 12 (lower plot).

APPENDIX D-1

AIR NEEDED TO REMOVE HEAT AND SUPPLY OXYGEN

A wide range of organic compounds shows little variation in the energy released per mass of O_2 used for complete oxidation to carbon dioxide and water. The mean value is approximately 14,000 kJ released/kg O_2 utilized. Using equation (iv) and the values of $\underline{h}_{out}$ from TABLE 1 (for approach R): $\frac{Q_v}{\underline{m}}$ = 362 kJ/kg dry air; thus it takes $\frac{14,000}{362}$ = 38.7 kg dry air to remove 14,000 kJ of released energy. Since there is 0.232 kg O_2/kg dry air, it takes 4.31 kg of dry air to replenish 1 kg of O_2. The ratio is $\frac{38.7}{4.31}$ = 8.98.

APPENDIX D-2

UNSUCCESSFUL ATTEMPT BY THE BELTSVILLE GROUP TO IMPROVE DRYING, IN ISOLATION FROM CONSIDERATIONS OF PROCESS DYNAMICS

In an attempt to improve drying, the "active stage" of the Beltsville Process was extended from the standard 21 day period to 28 days, and on day 14 ventilation was switched from the vacuum-induced to the forced pressure direction and increased by approximately 4-fold (10). The modified process behaved as follows. During the first 14 days the average peak interior temperature was 70°C. The increase in ventilation on day 14 marked the onset of a cooling trend, such that on day 21 the average temperature was 42°C. (In conventional Beltsville operation the temperature remains at peak, or near peak, values throughout the 21 day period.) This modification yielded only a modest improvement in water removal. The initial moisture content of 63.6% decreased to 52.1% in the 28 day period, compared to a terminal value of 56.3% obtained in the usual 21 day period through conventional operation.

This behavior is predictable based on expression iv, as constrained by the interaction between heat generation and temperature. As is characteristic of the Beltsville Process, a small $\underline{m}$ resulted in a temperature ascent to biologically inhibitive levels. Once peak temperatures were reached (∼day 5) $\underline{h}_{out}$ was large but the resultant Q_v was small, as evidenced by the small moisture content decrease. Increasing $\underline{m}$ on day 14 cooled the pile because the rate of biological activity (≡heat generation) could not sustain the peak temperature against the increased rate of heat removal. The decreasing outlet temperatures were accompanied by decreasing values of $\underline{h}_{out}$. As predicted the resultant Q_v was small, judged by the small moisture content decrement.

APPENDIX E

Temperature Observations

Pile 12

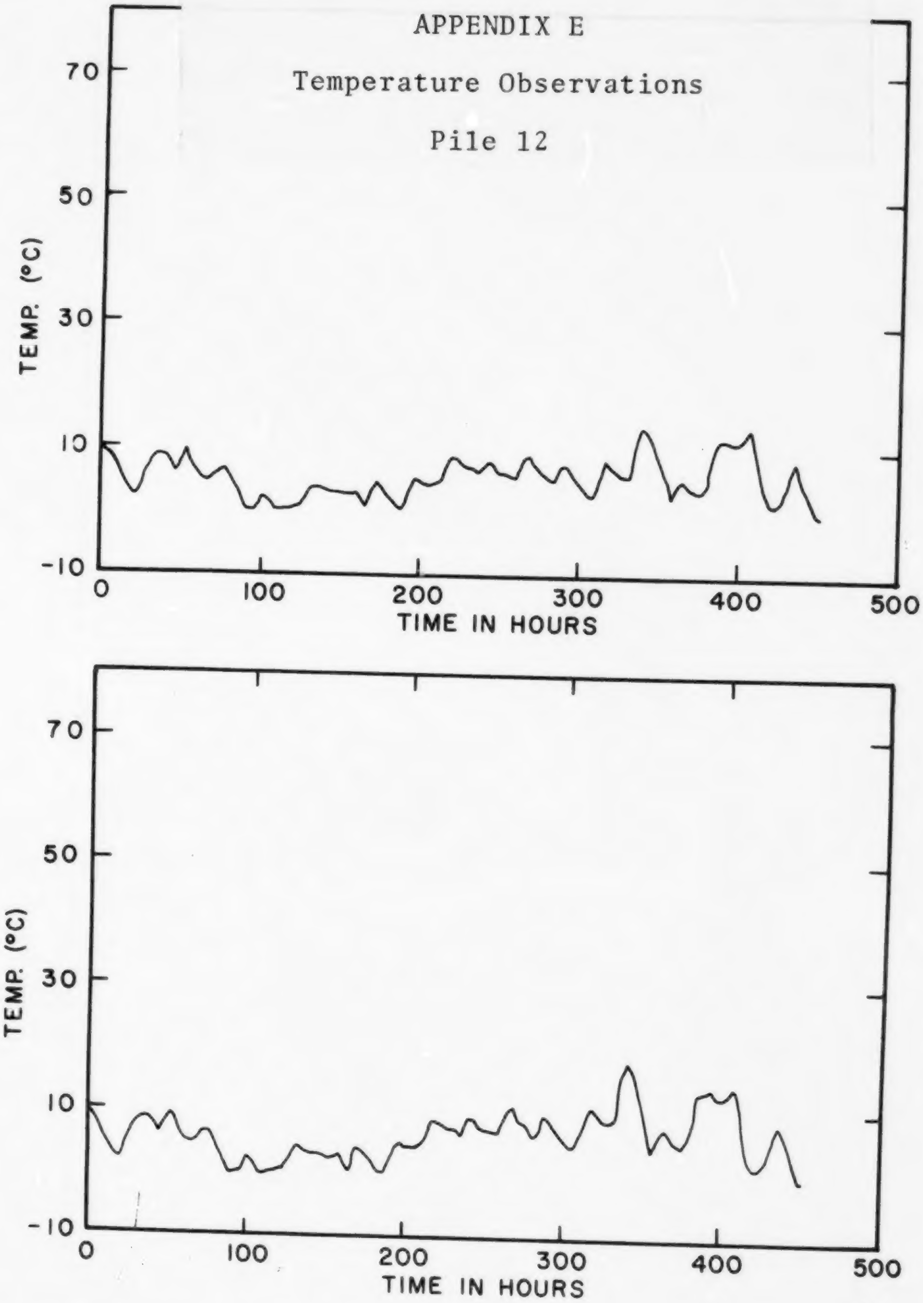


Figure 149. Pile 12, temperature at position 1 (upper plot) and position 2 (lower plot).

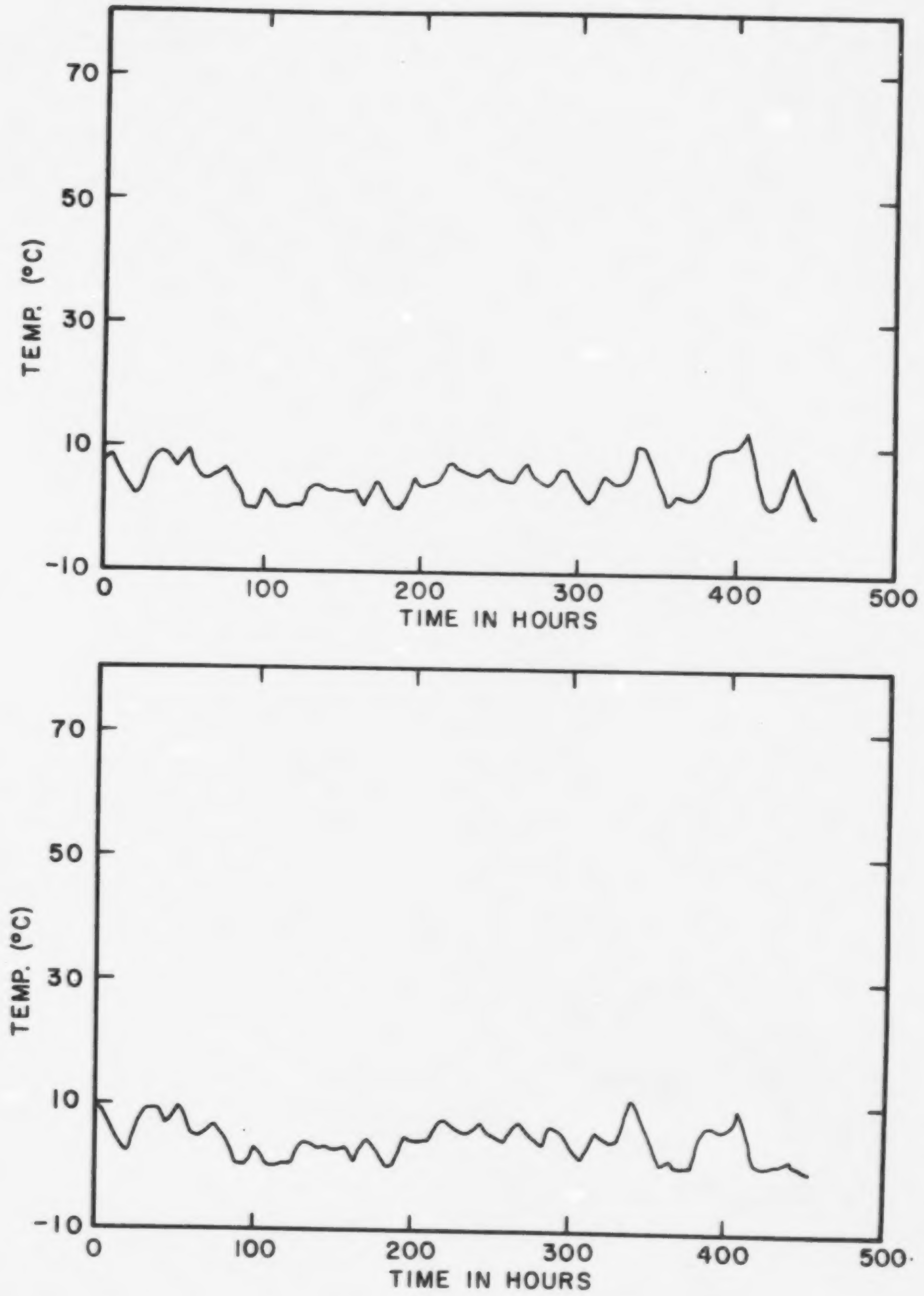


Figure 150. Pile 12, temperature at position 3 (upper plot) and position 4 (lower plot).

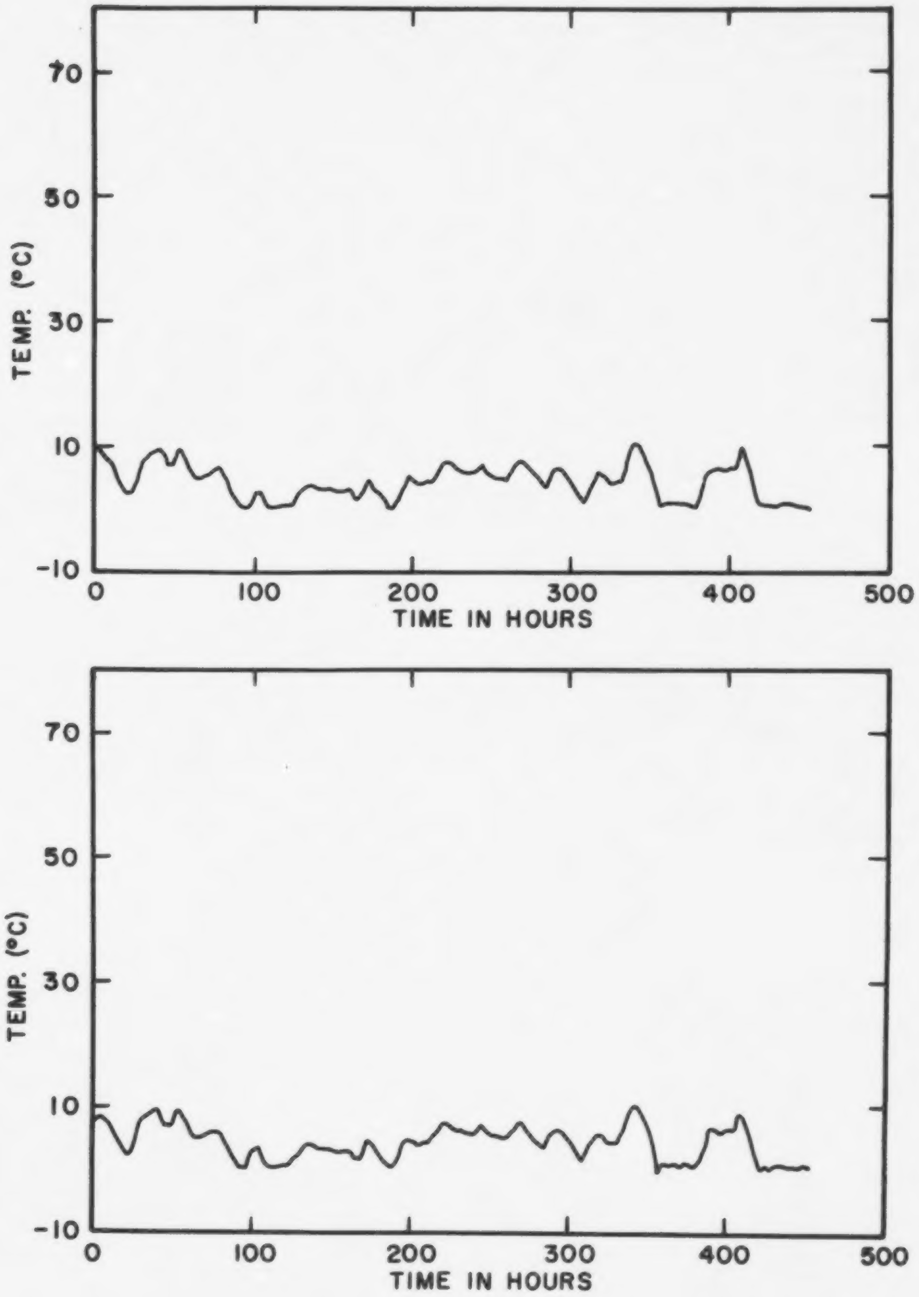


Figure 151. Pile 12, temperature at position 5 (upper plot) and position 6 (lower plot).

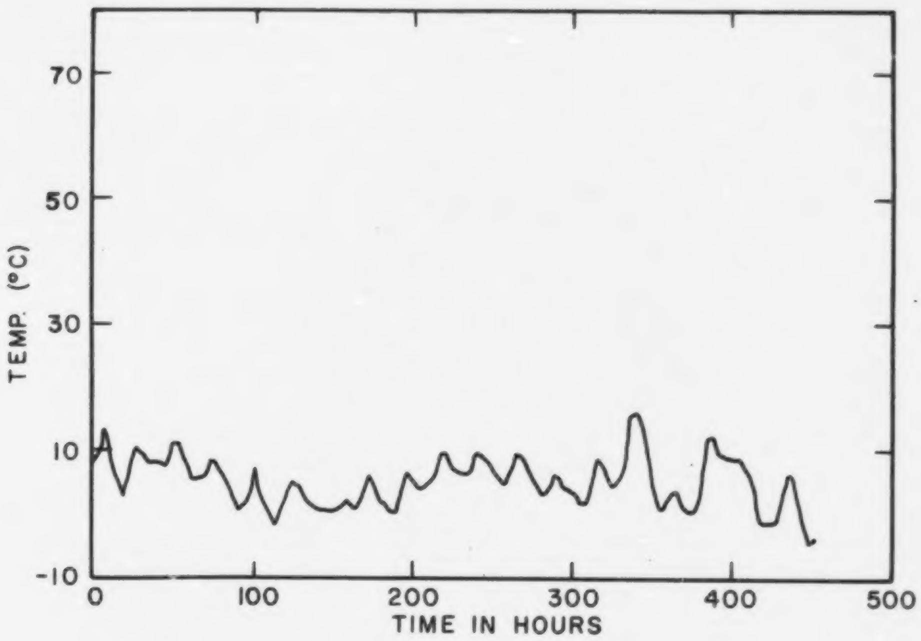


Figure 152. Ambient temperature during the experimental period for pile 12.

APPENDIX F

Observations on Blower Operation, Temperature, O_2, CO_2, pH, and Moisture Content for Piles 6A, 6B, and 6C

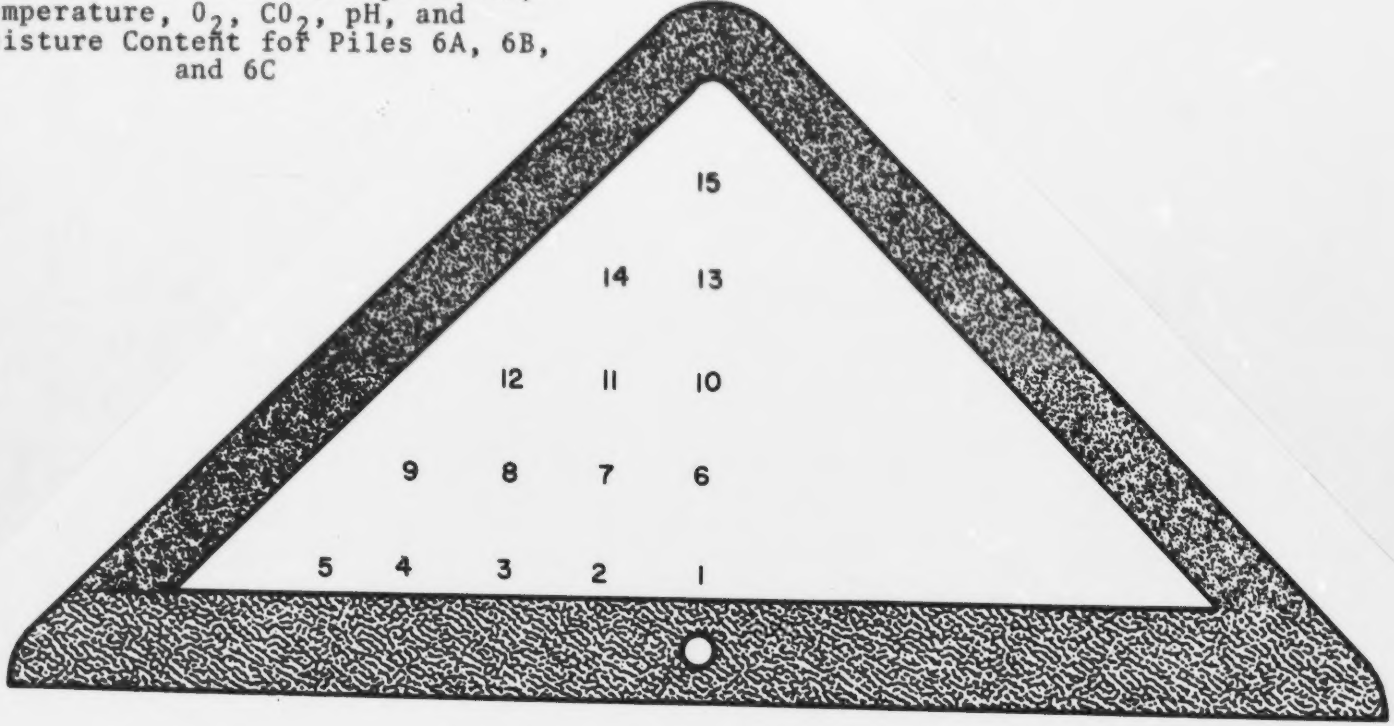


Figure 153. Piles 6A, 6B, and 6C, cross-sectional representation: textured area, woodchip cover and base; clear area, sludge-woodchip mixture; circle, perforated flex-hose. The numbers indicate monitoring and control positions: thermocouples, positions 1 through 15; gas sampling probes, adjacent to position 13 (also adjacent to position 6 in pile 6A); control thermistor, between positions 1 and 6. The blower was operated in the forced-pressure mode.

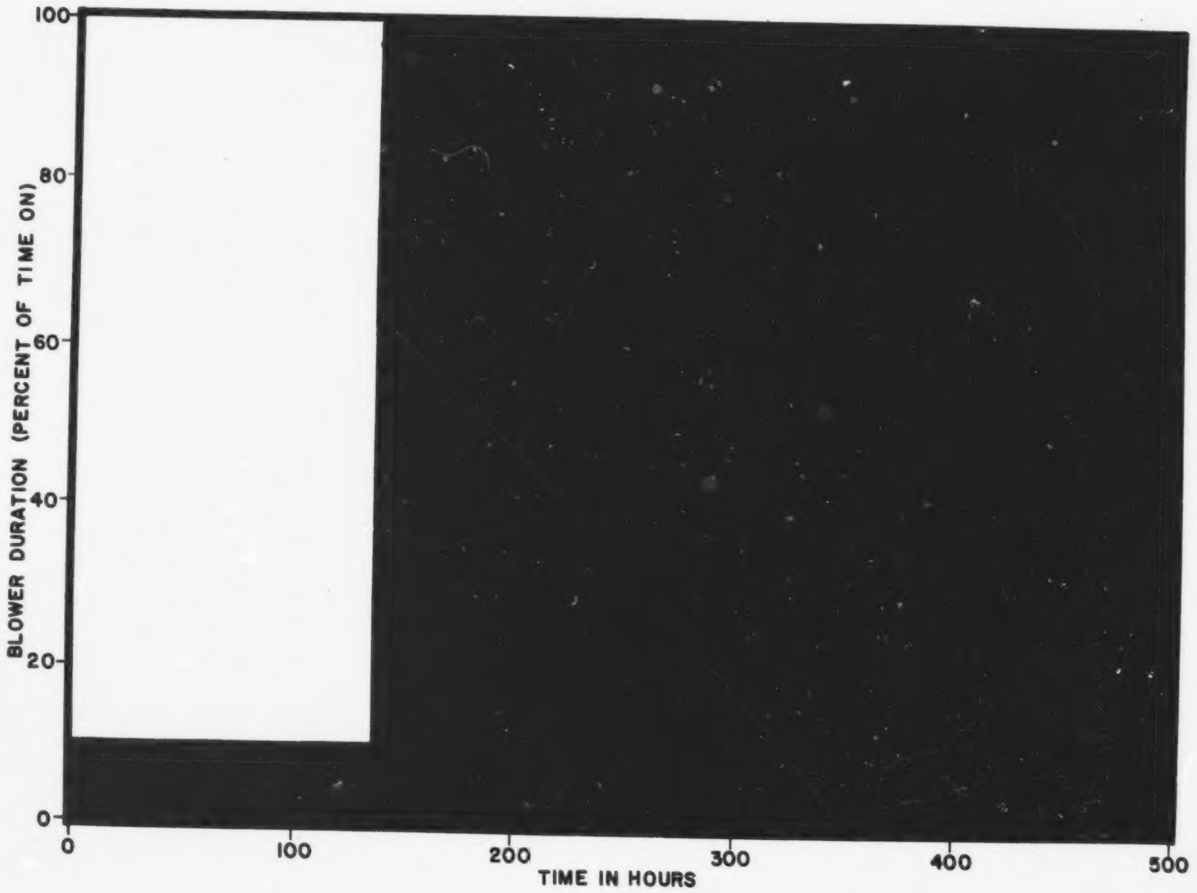


Figure 154. Pile 6A, blower operation. The baseline represents operation as scheduled by timer, and the area above the baseline represents operation through the temperature feedback control system. The blower was operated in the forced pressure mode.

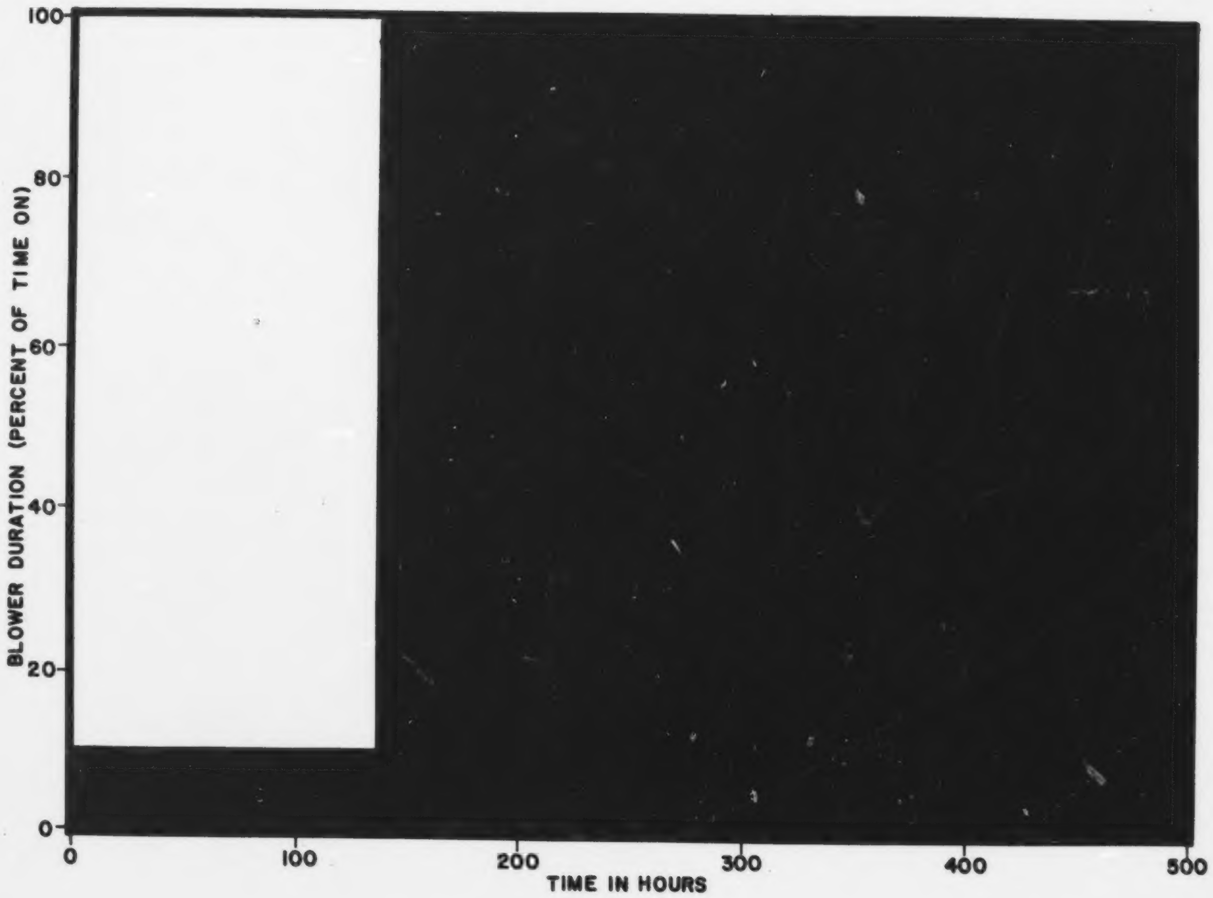


Figure 155. Pile 6B, blower operation. The baseline represents operation as scheduled by timer, and the area above the baseline represents operation through the temperature feedback control system. The blower was operated in the forced pressure mode.

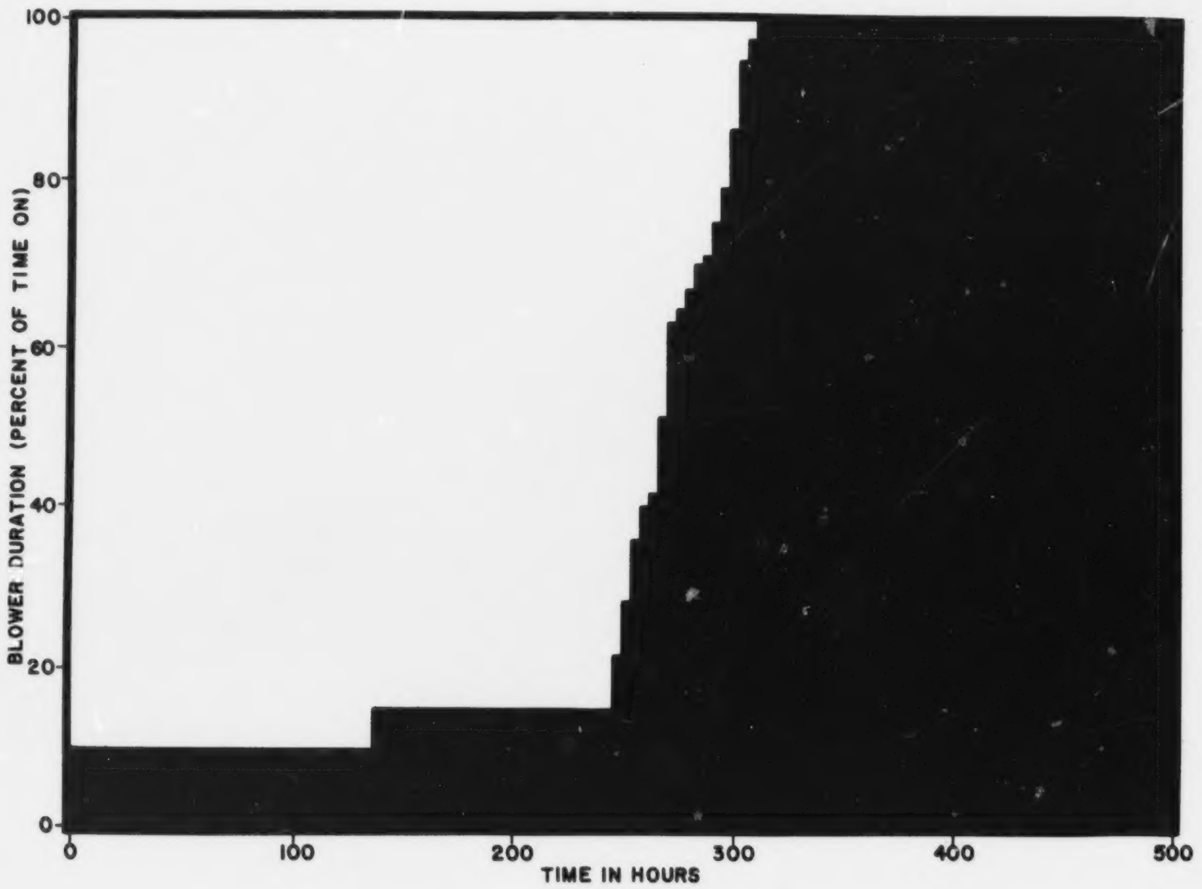


Figure 156. Pile 6C, blower operation. The baseline represents operation as scheduled by timer, and the area above the baseline represents operation through the temperature feedback control system. The blower was operated in the forced pressure mode.

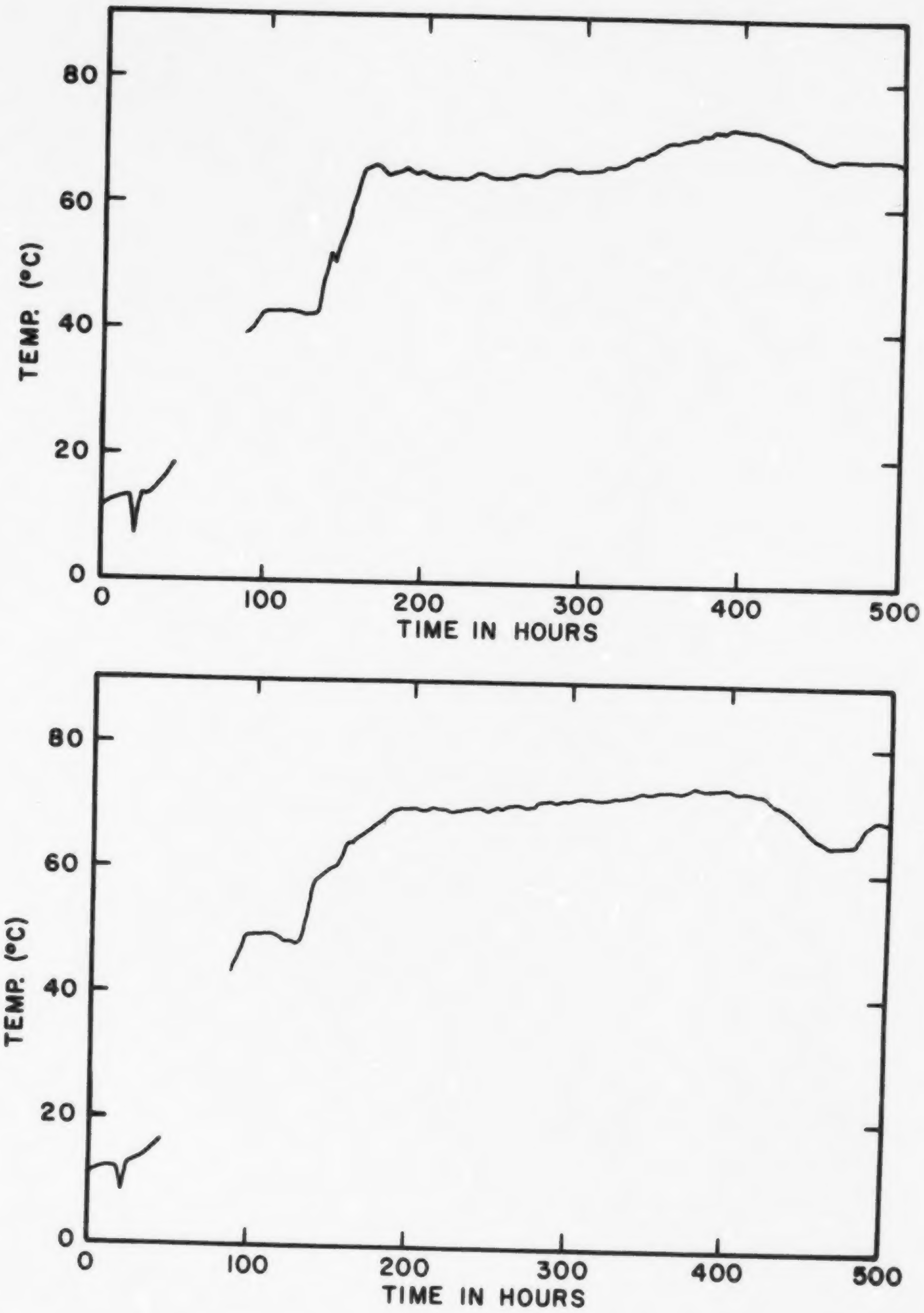


Figure 157. Pile 6A, temperature at position 1 (upper plot) and position 2 (lower plot).

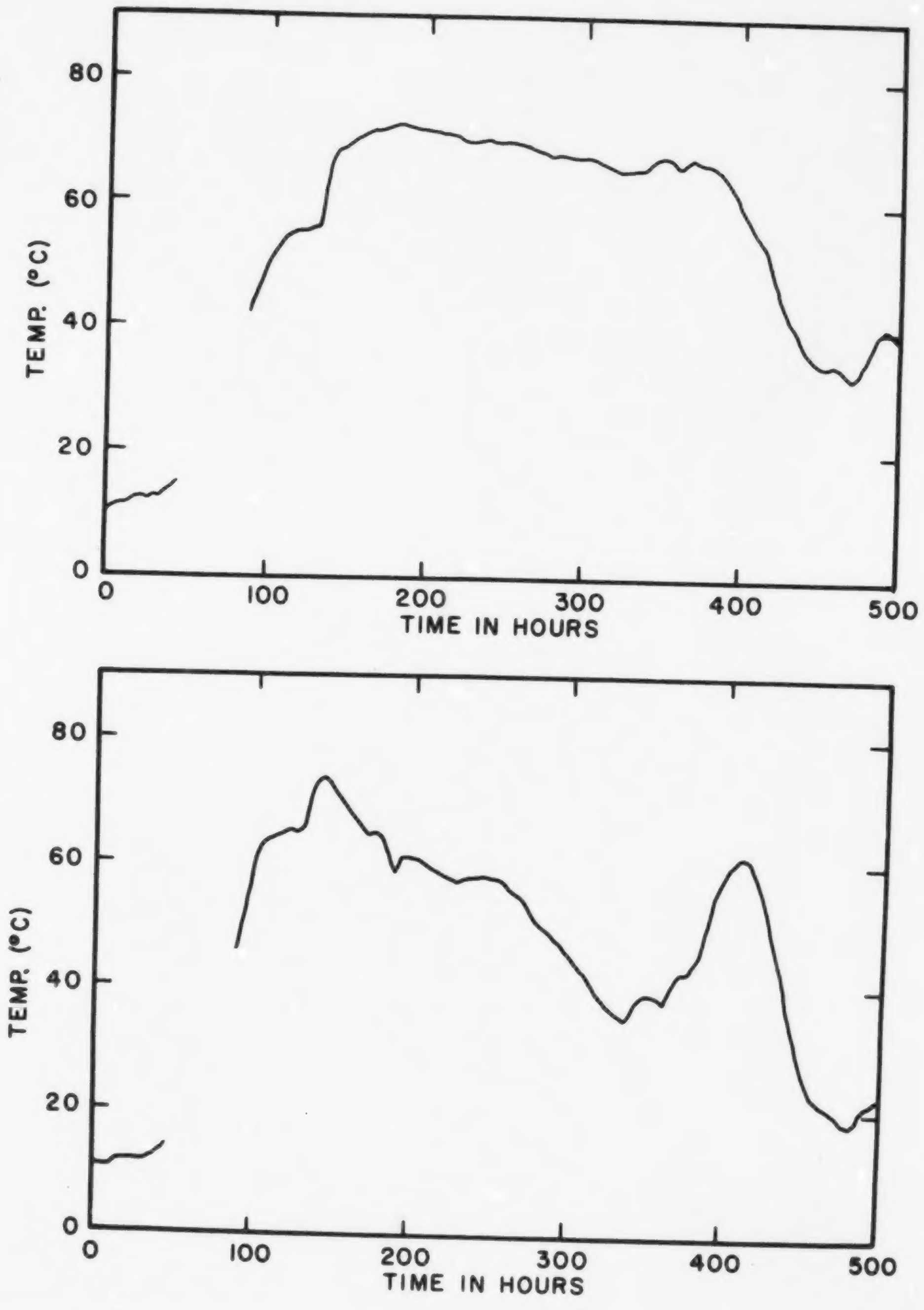


Figure 158. Pile 6A, temperature at position 3 (upper plot) and position 4 (lower plot).

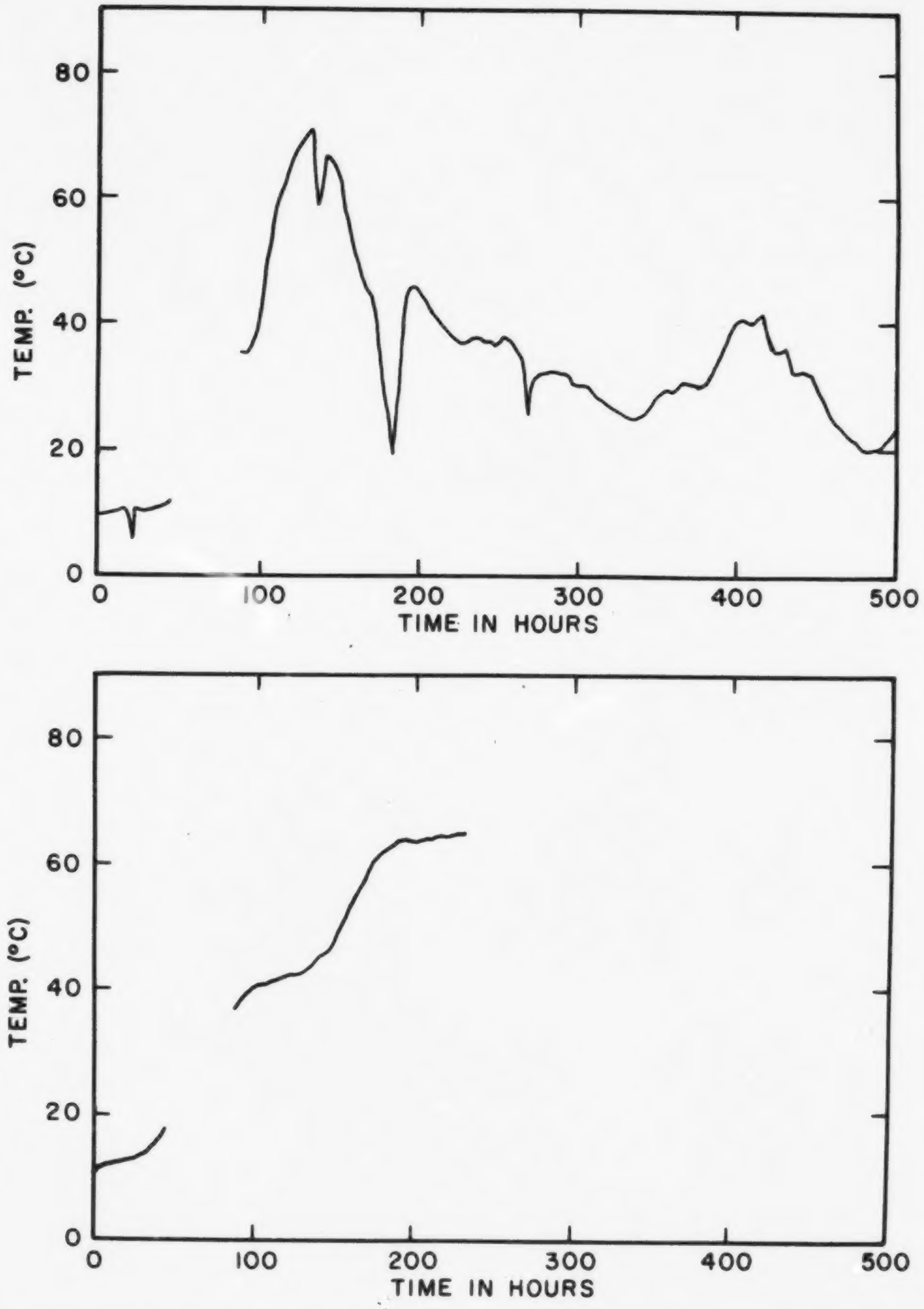


Figure 159. Pile 6A, temperature at position 5 (upper plot) and position 6 (lower plot).

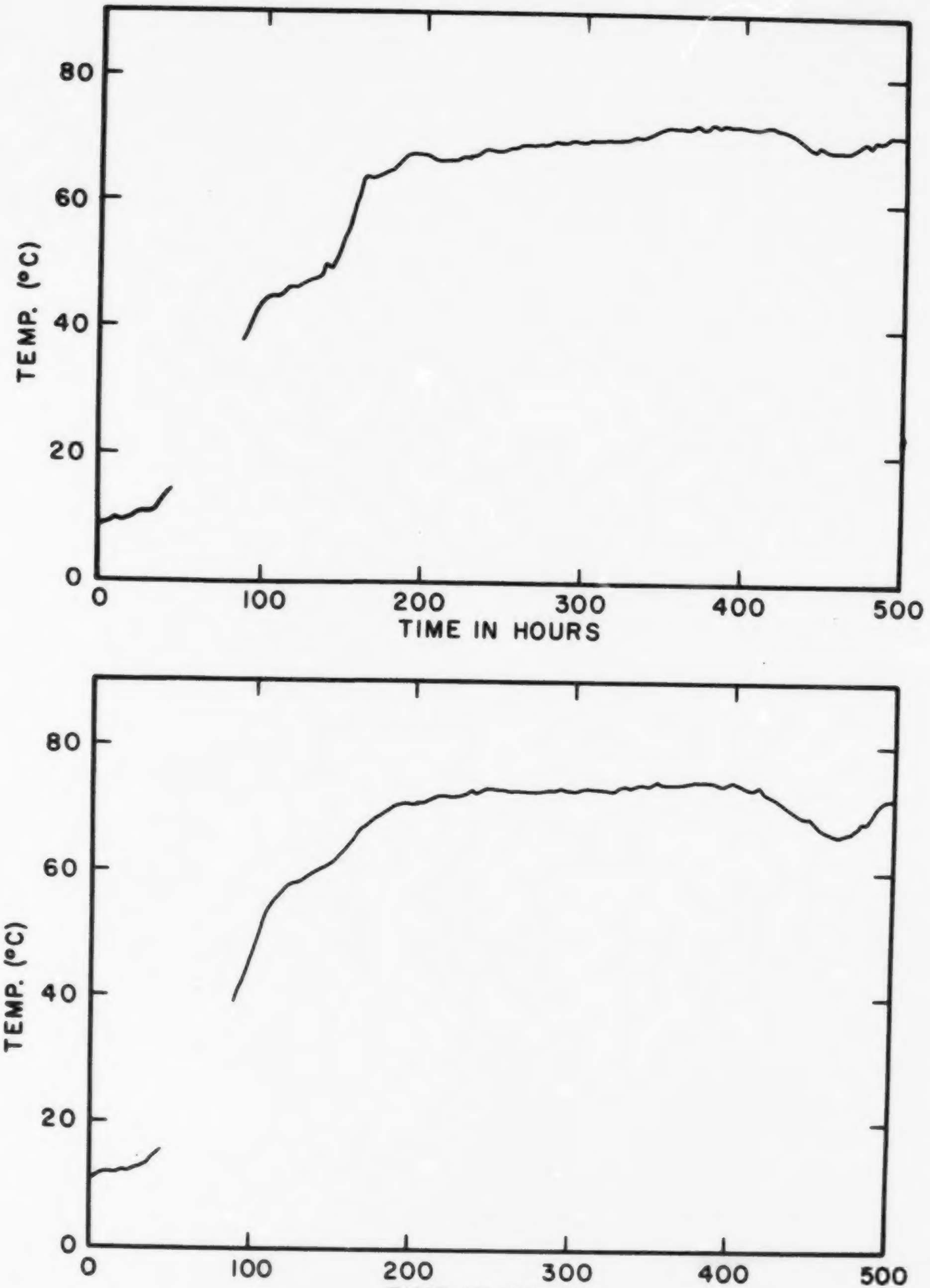


Figure 160. Pile 6A, temperature at position 7 (upper plot) and position 8 (lower plot).

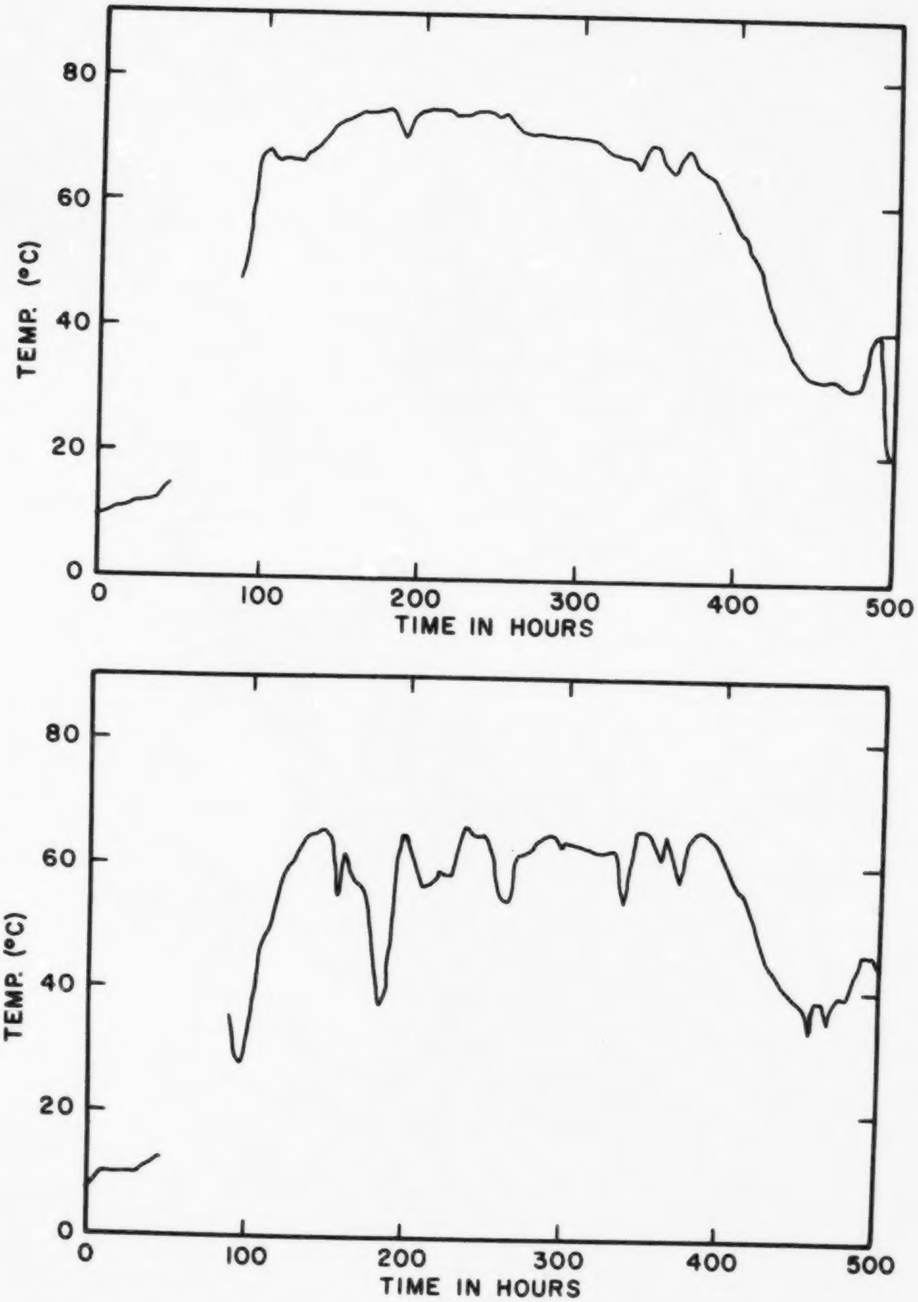


Figure 161. Pile 6A, temperature at position 9 (upper plot) and position 12 (lower plot).

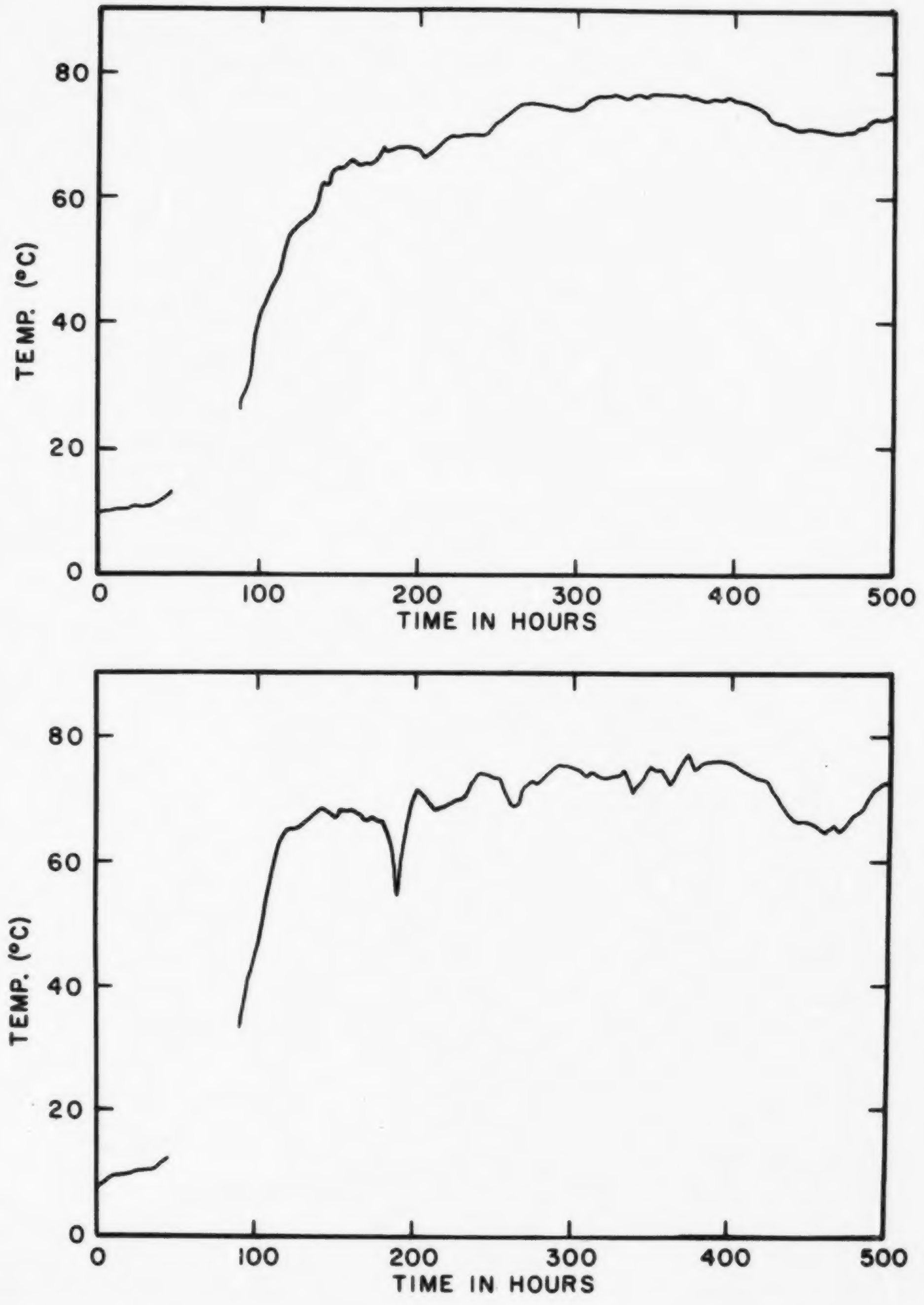


Figure 162. Pile 6A, temperature at position 13 (upper plot) and position 14 (lower plot).

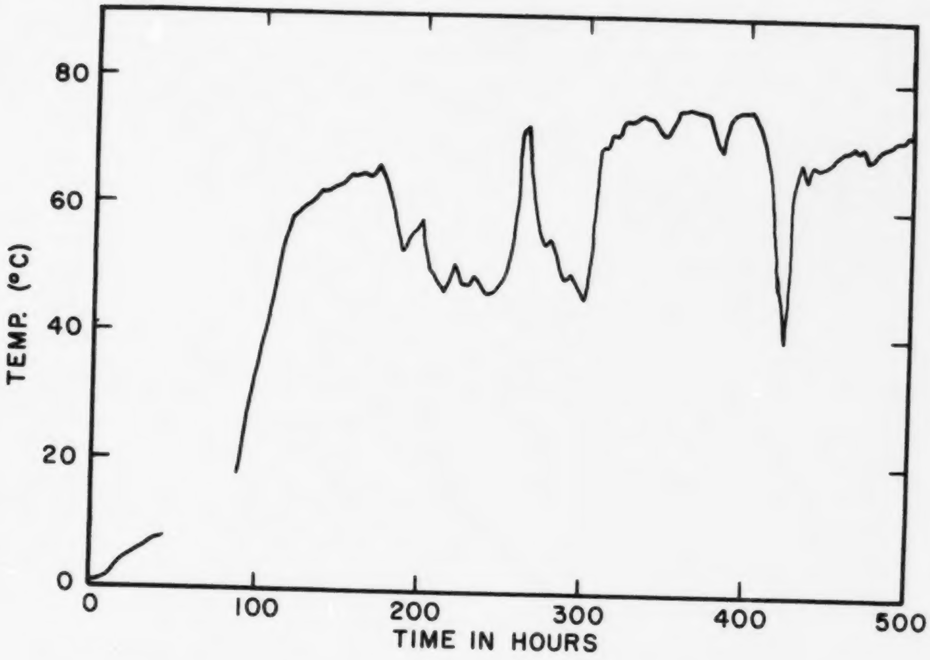


Figure 163. Pile 6A, temperature at position 15.

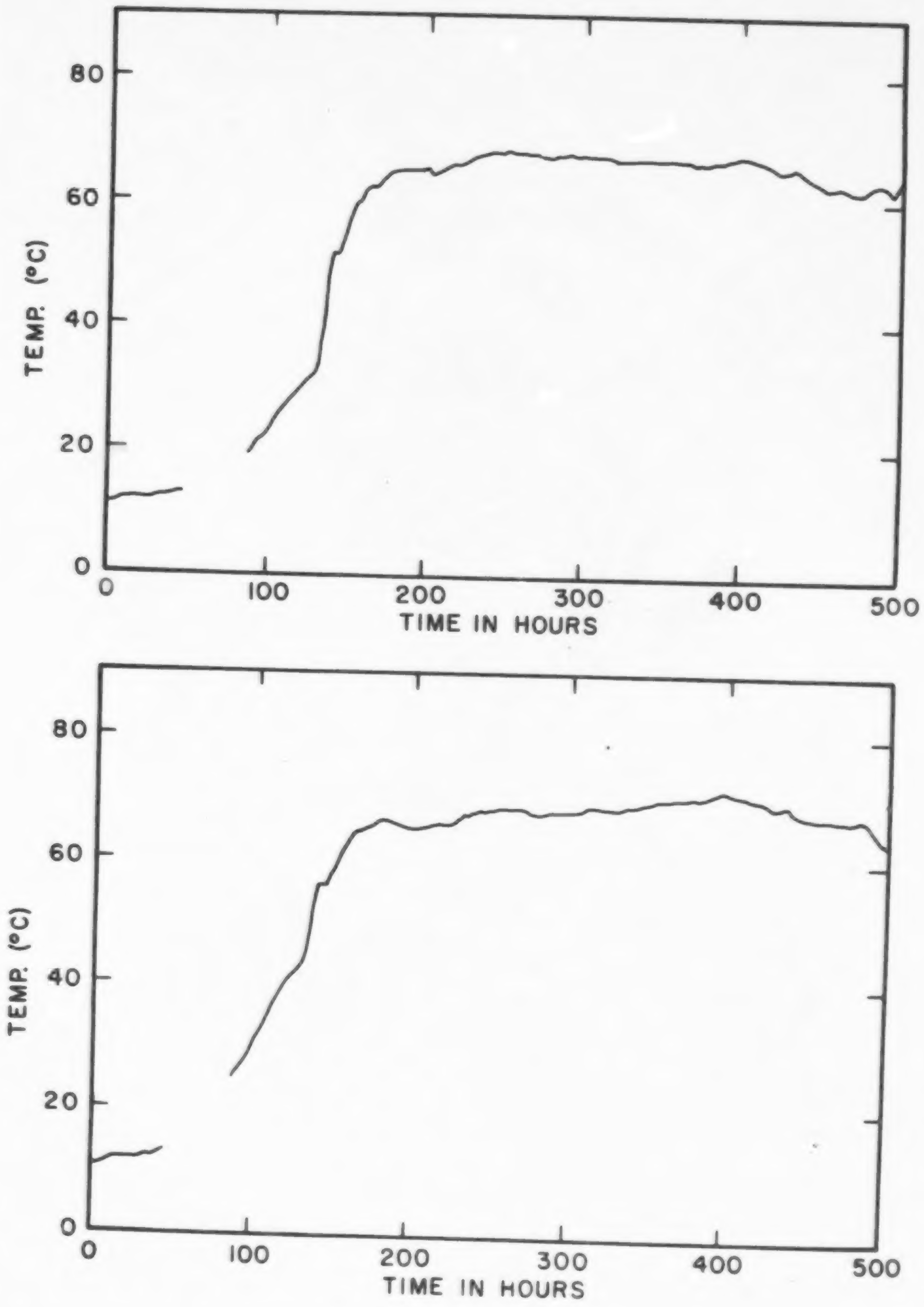


Figure 164. Pile 6B, temperature at position 1 (upper plot) and position 2 (lower plot).

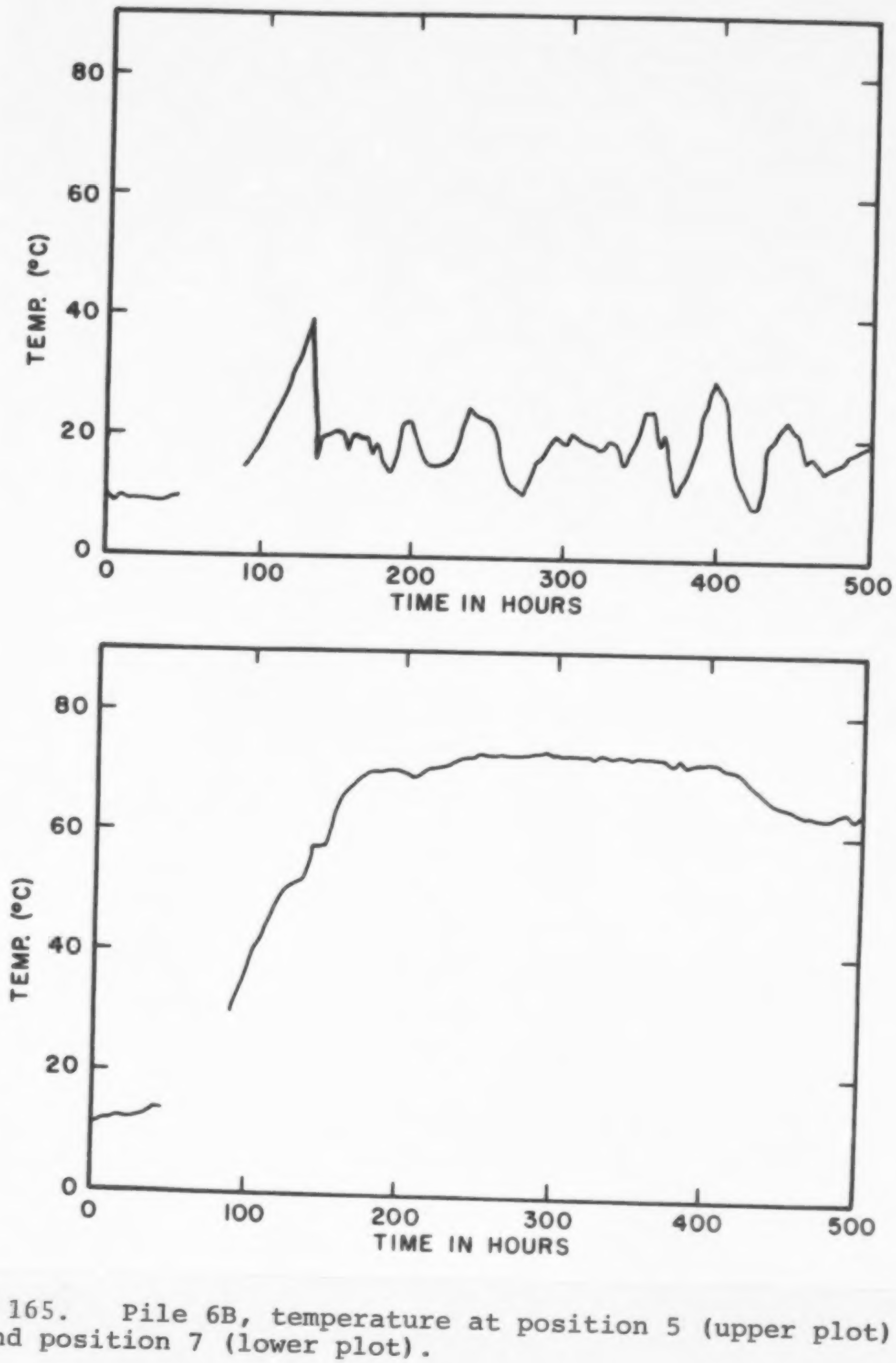


Figure 165. Pile 6B, temperature at position 5 (upper plot) and position 7 (lower plot).

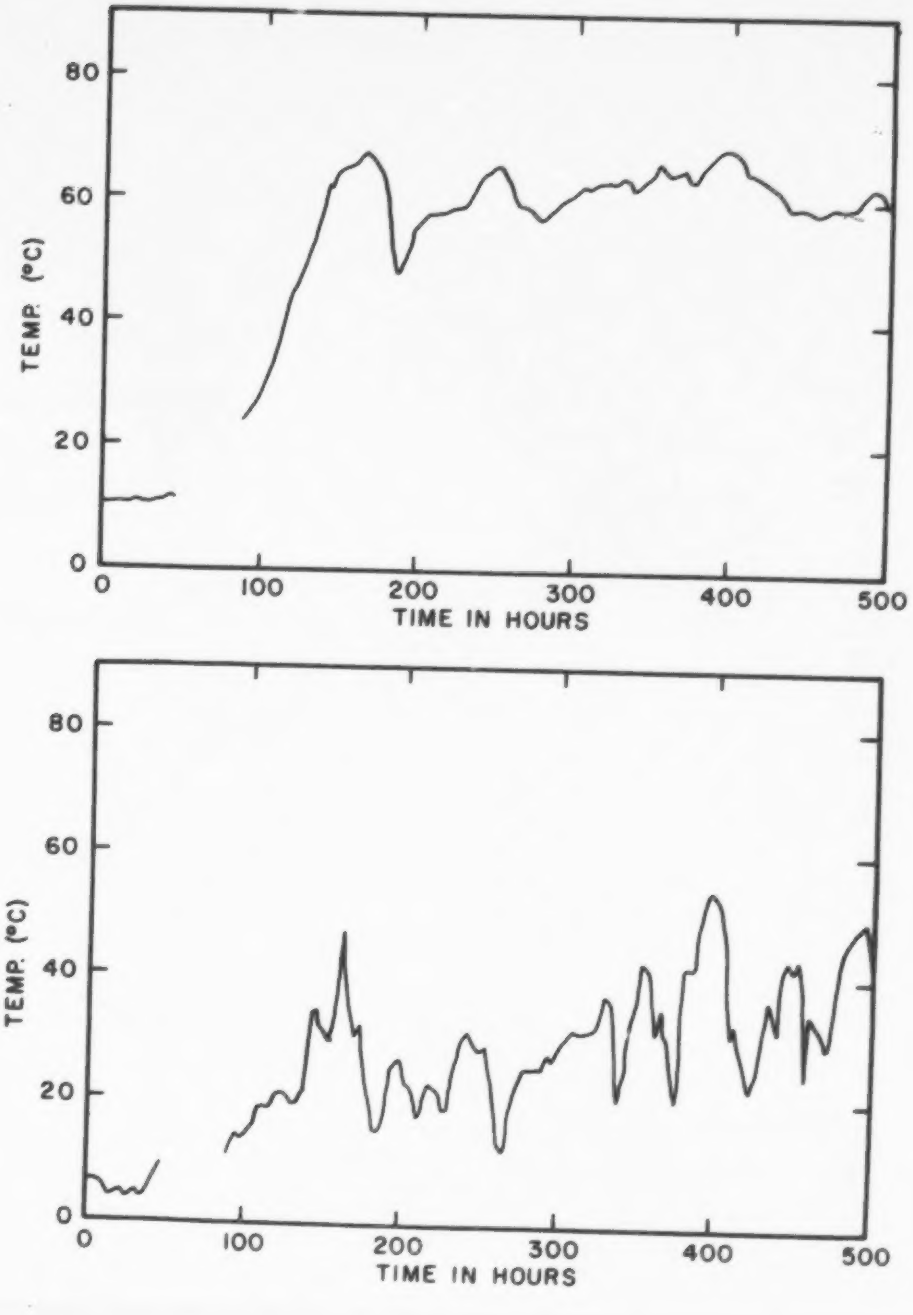


Figure 166. Pile 6B, temperature at position 9 (upper plot) and position 12 (lower plot).

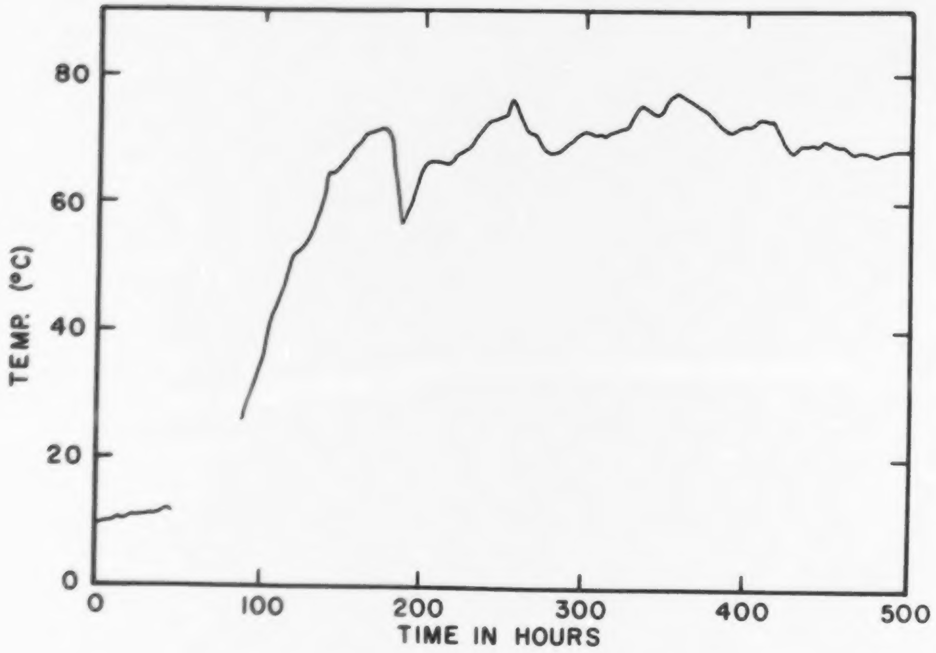


Figure 167. Pile 6B, temperature at position 13.

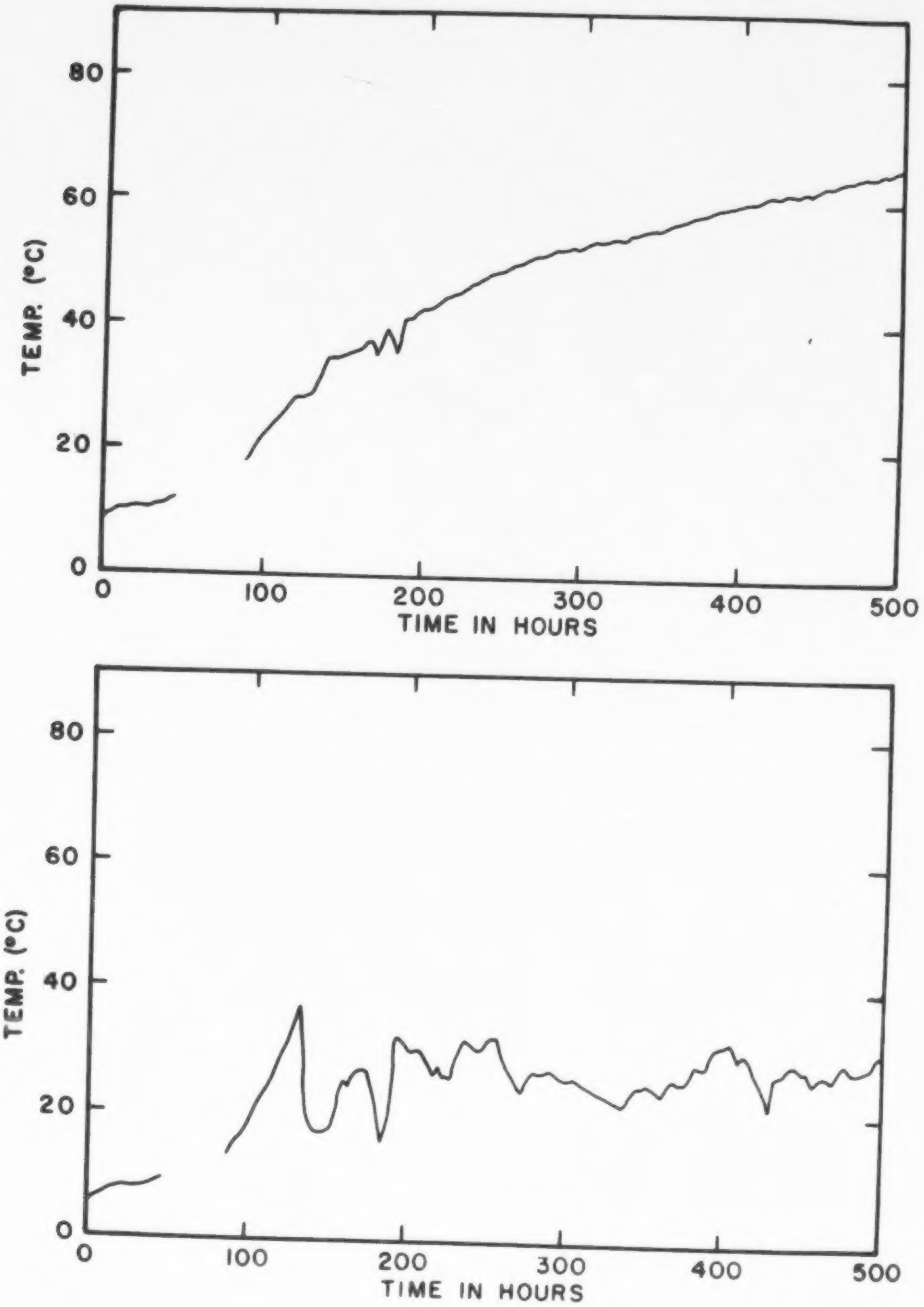


Figure 168. Pile 6C, temperature at position 2 (upper plot) and position 5 (lower plot).

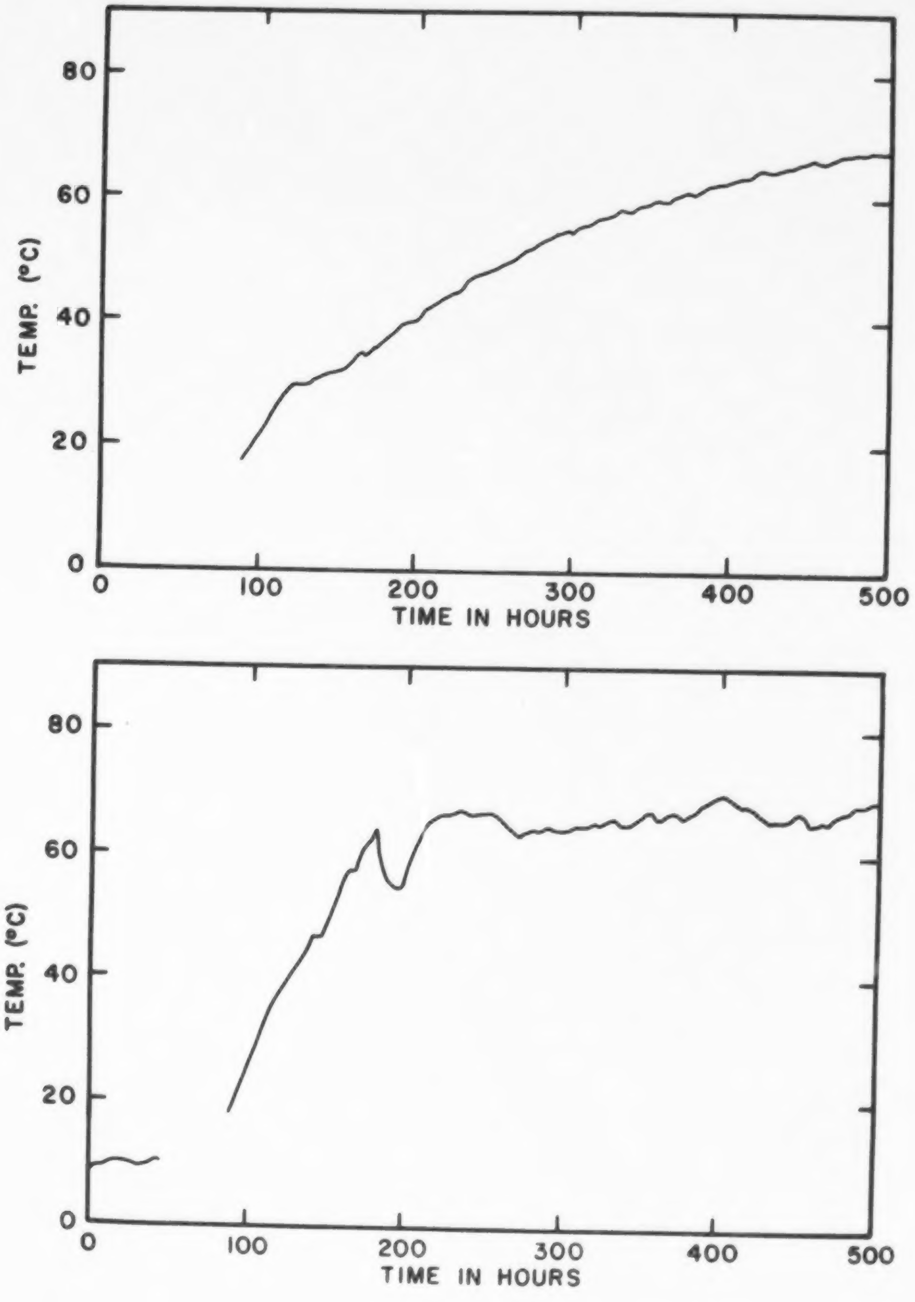


Figure 169. Pile 6C, temperature at position 7 (upper plot) and position 9 (lower plot).

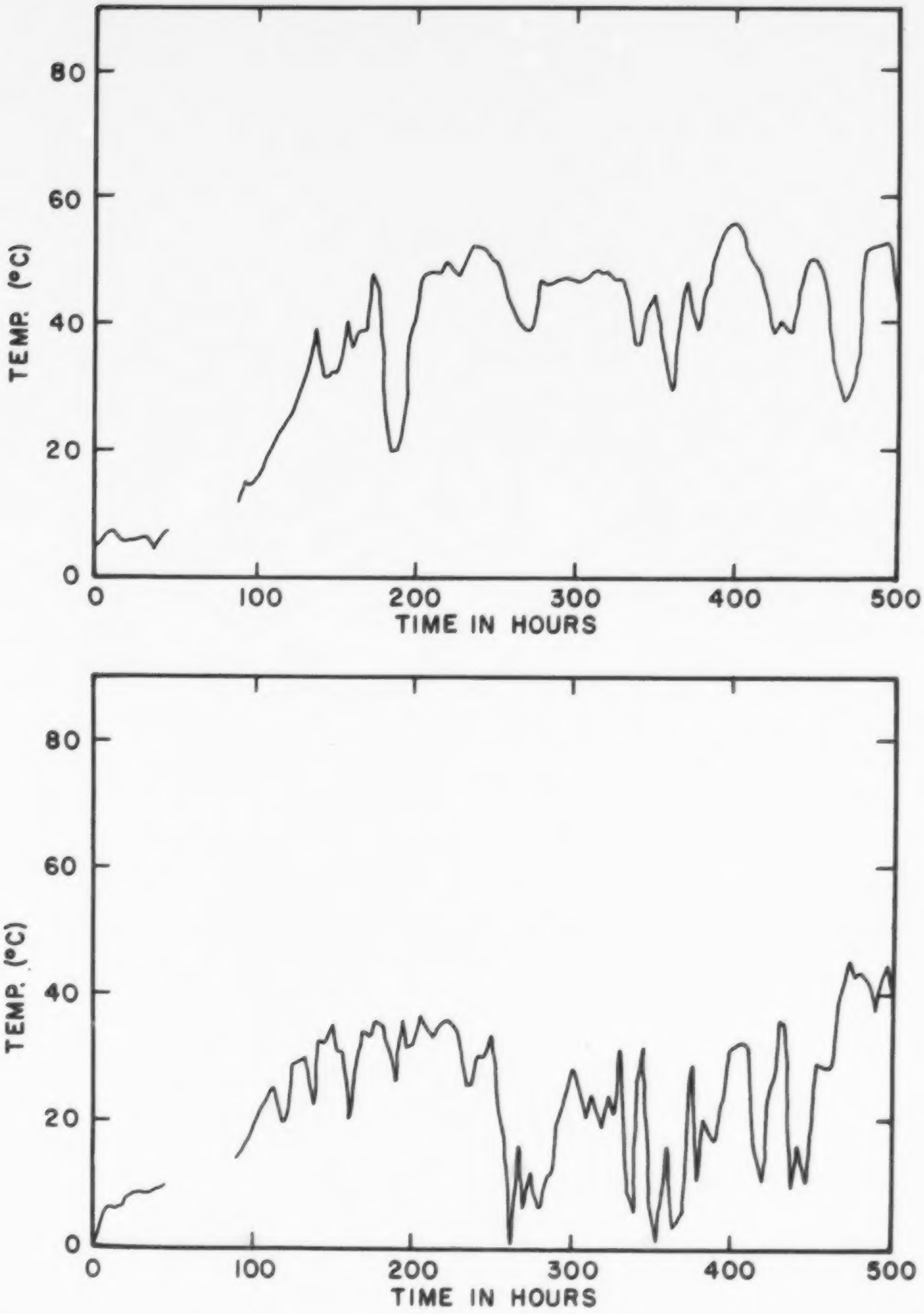


Figure 170. Pile 6C, temperature at position 12 (lower plot) and position 13 (upper plot).

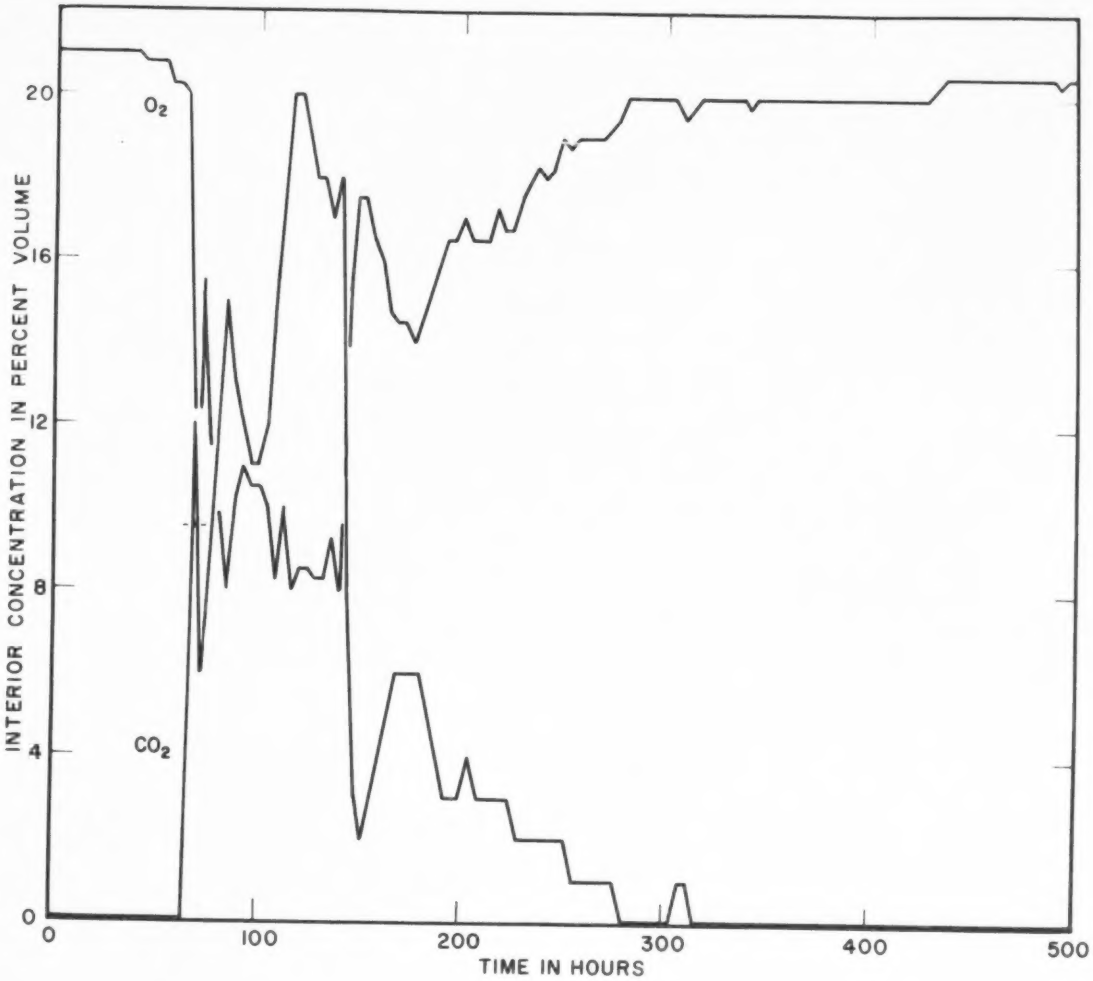


Figure 171. Pile 6A, concentrations of 0_2 (upper plot) and $C0_2$ (lower plot). The gas sampling probe was adjacent to position 6.

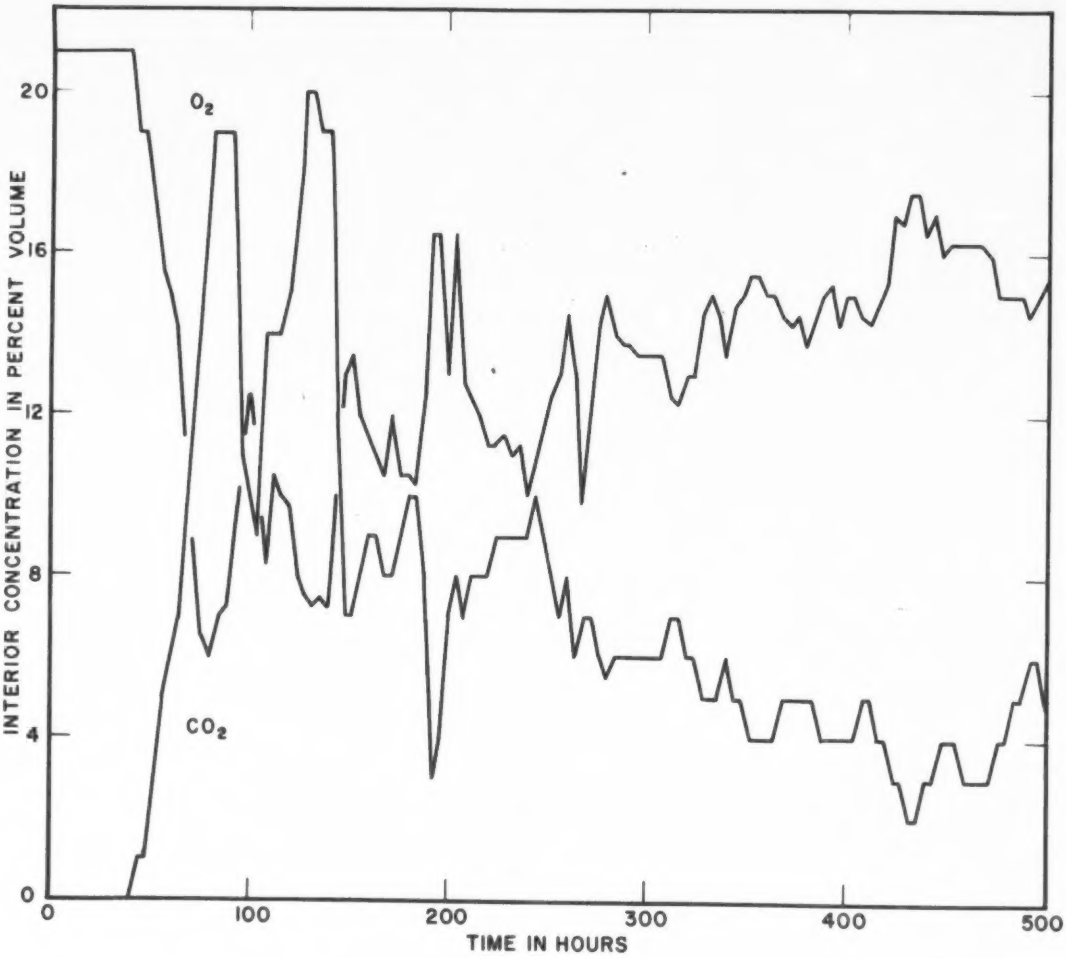


Figure 172. Pile 6A, concentrations of 0_2 (upper plot) and $C0_2$ (lower plot). The gas sampling probe was adjacent to position 13.

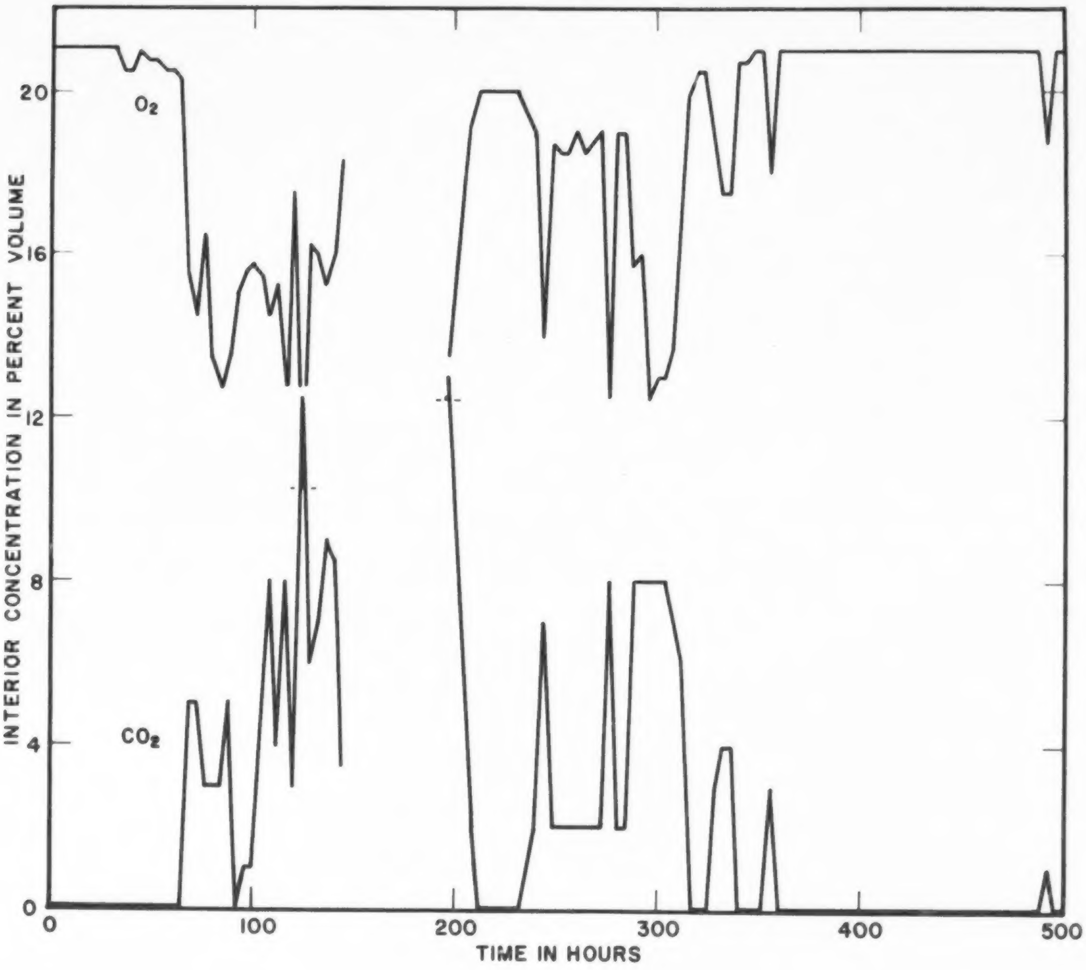


Figure 173. Pile 6B, concentrations of O_2 (upper plot) and CO_2 (lower plot). The gas sampling probe was adjacent to position 13.

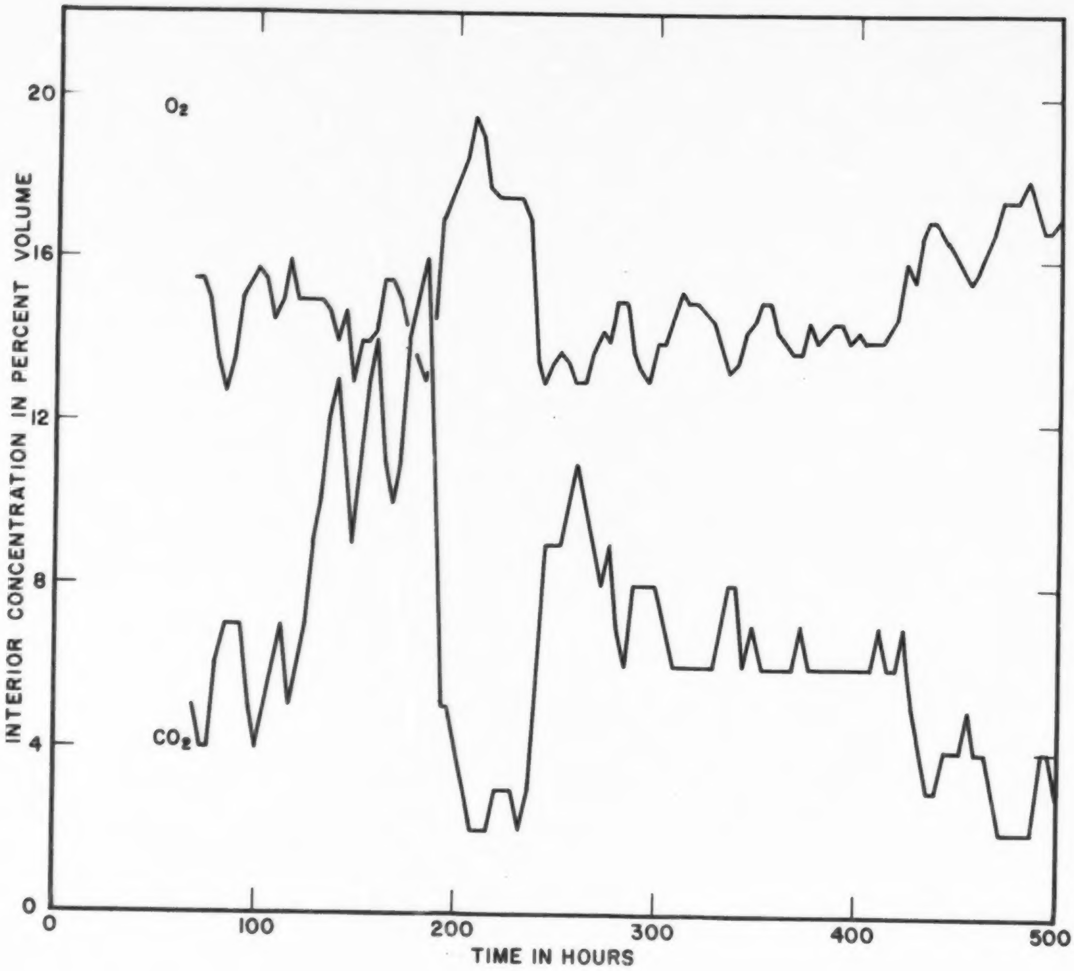


Figure 174. Pile 6C, concentrations of 0_2 (upper plot) and $C0_2$ (lower plot). The gas sampling probe was adjacent to position 13.

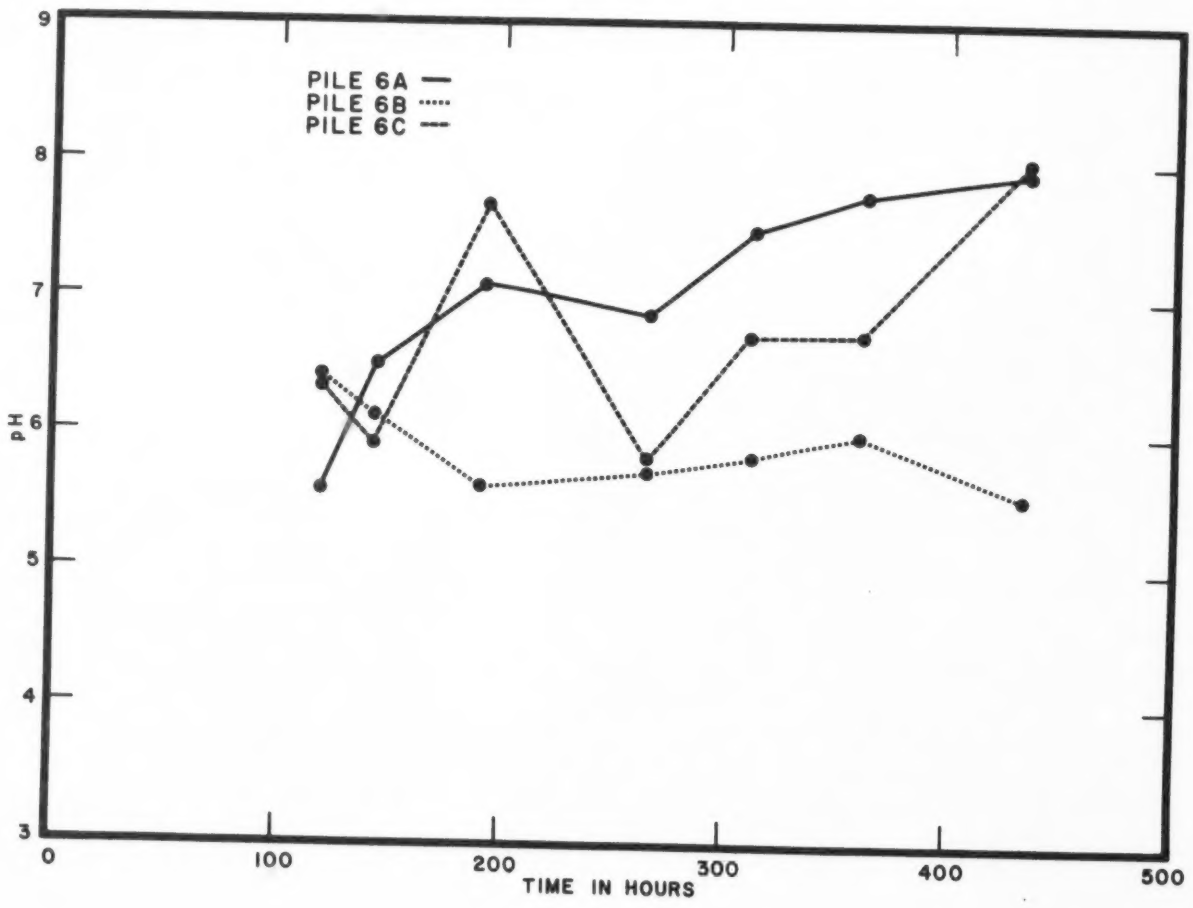


Figure 175. Piles 6A, 6B, and 6C, pH. The samples were from interior locations.

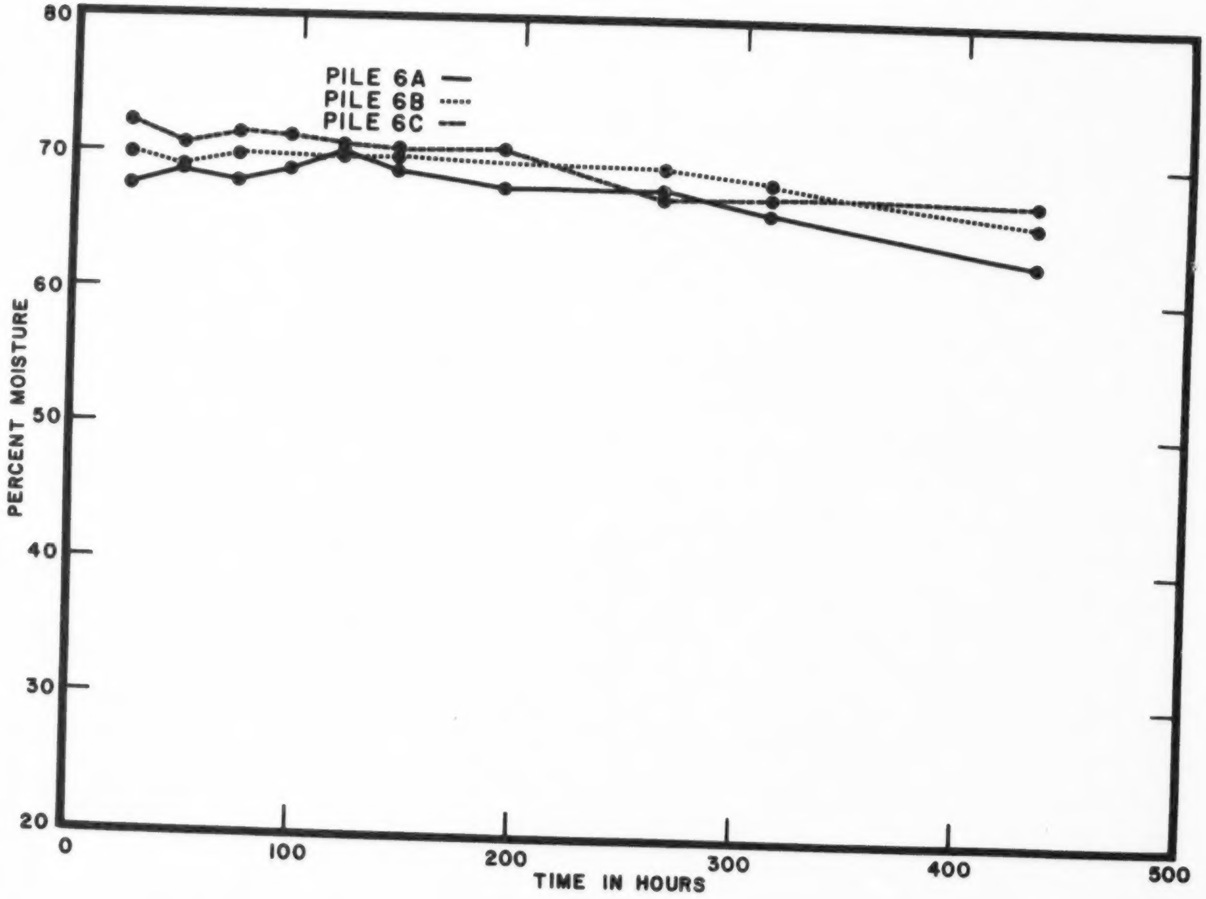


Figure 176. Piles 6A, 6B, and 6C, moisture content. The samples were from interior locations.

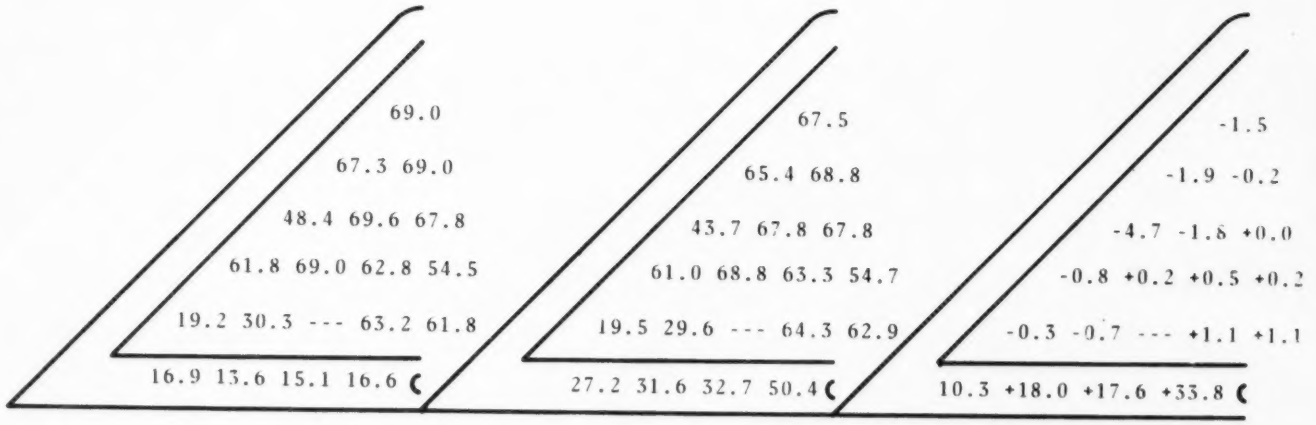

69.0
67.3 69.0
48.4 69.6 67.8
61.8 69.0 62.8 54.5
19.2 30.3 --- 63.2 61.8
16.9 13.6 15.1 16.6 ☾
67.5
65.4 68.8
43.7 67.8 67.8
61.0 68.8 63.3 54.7
19.5 29.6 --- 64.3 62.9
27.2 31.6 32.7 50.4 ☾
-1.5
-1.9 -0.2
-4.7 -1.8 +0.0
-0.8 +0.2 +0.5 +0.2
-0.3 -0.7 --- +1.1 +1.1
10.3 +18.0 +17.6 +33.8 ☾

Figure 177. Pile 6B, special terminal test of air penetration. Temperature (^{o}C) immediately prior to the introduction of heated air, left hand cross-section; temperature 30 min after start of introduction of heated air, middle cross-section; temperature differential, right hand cross-section.

APPENDIX G

Temperature Observations

Pile 13

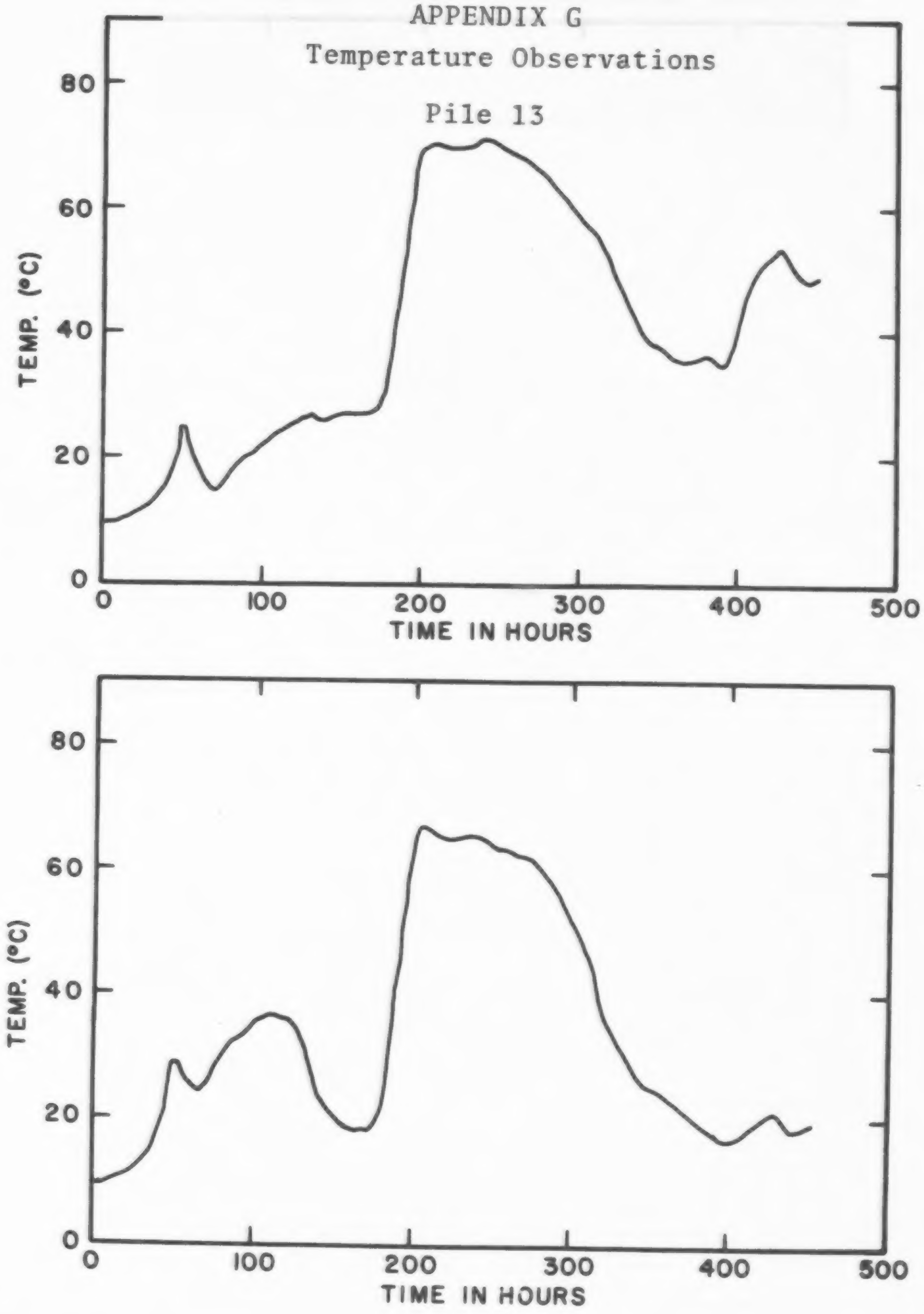


Figure 178. Pile 13, temperature at position 1 (upper plot) and position 2 (lower plot).

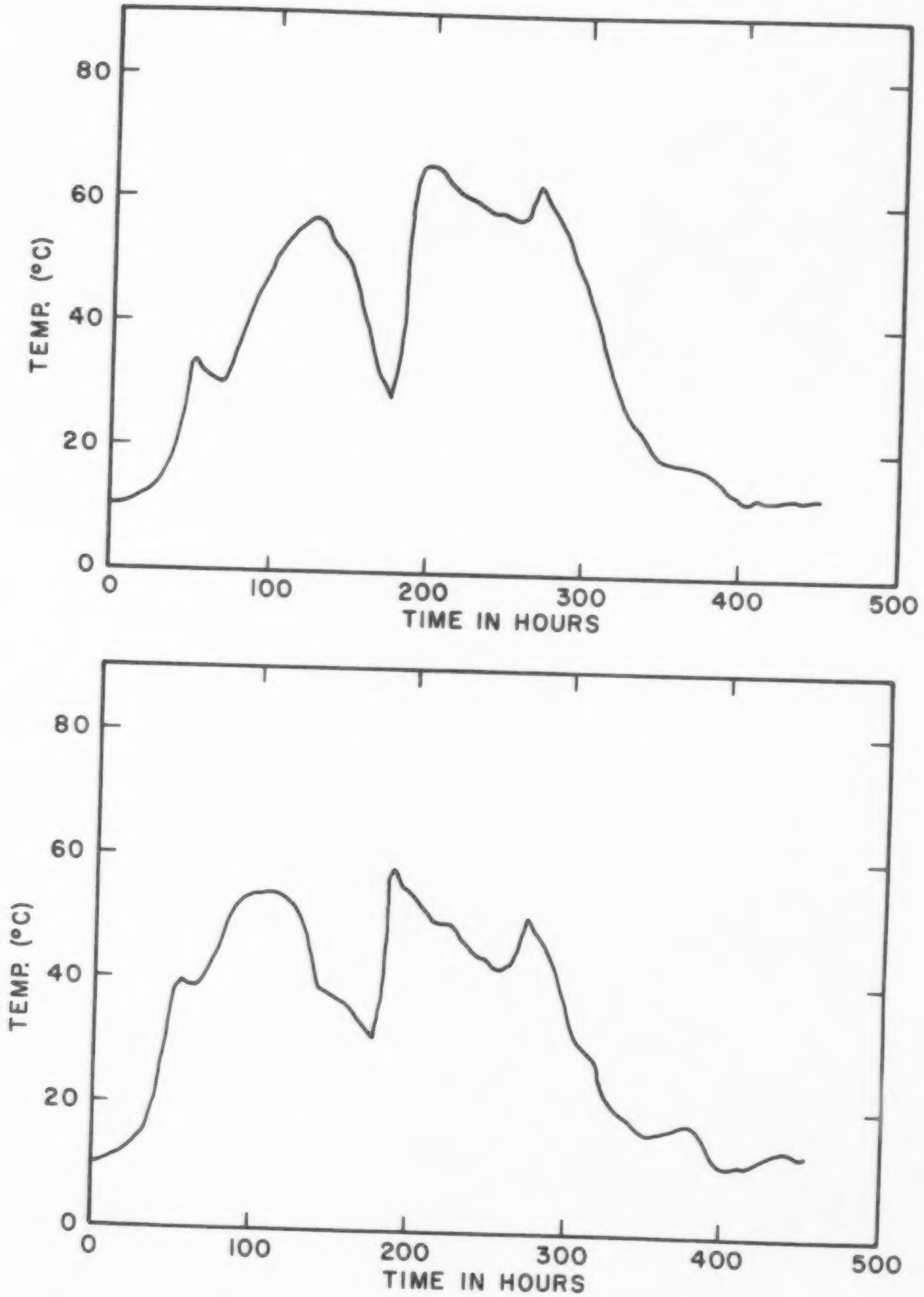


Figure 179. Pile 13, temperature at position 3 (upper plot) and position 4 (lower plot).

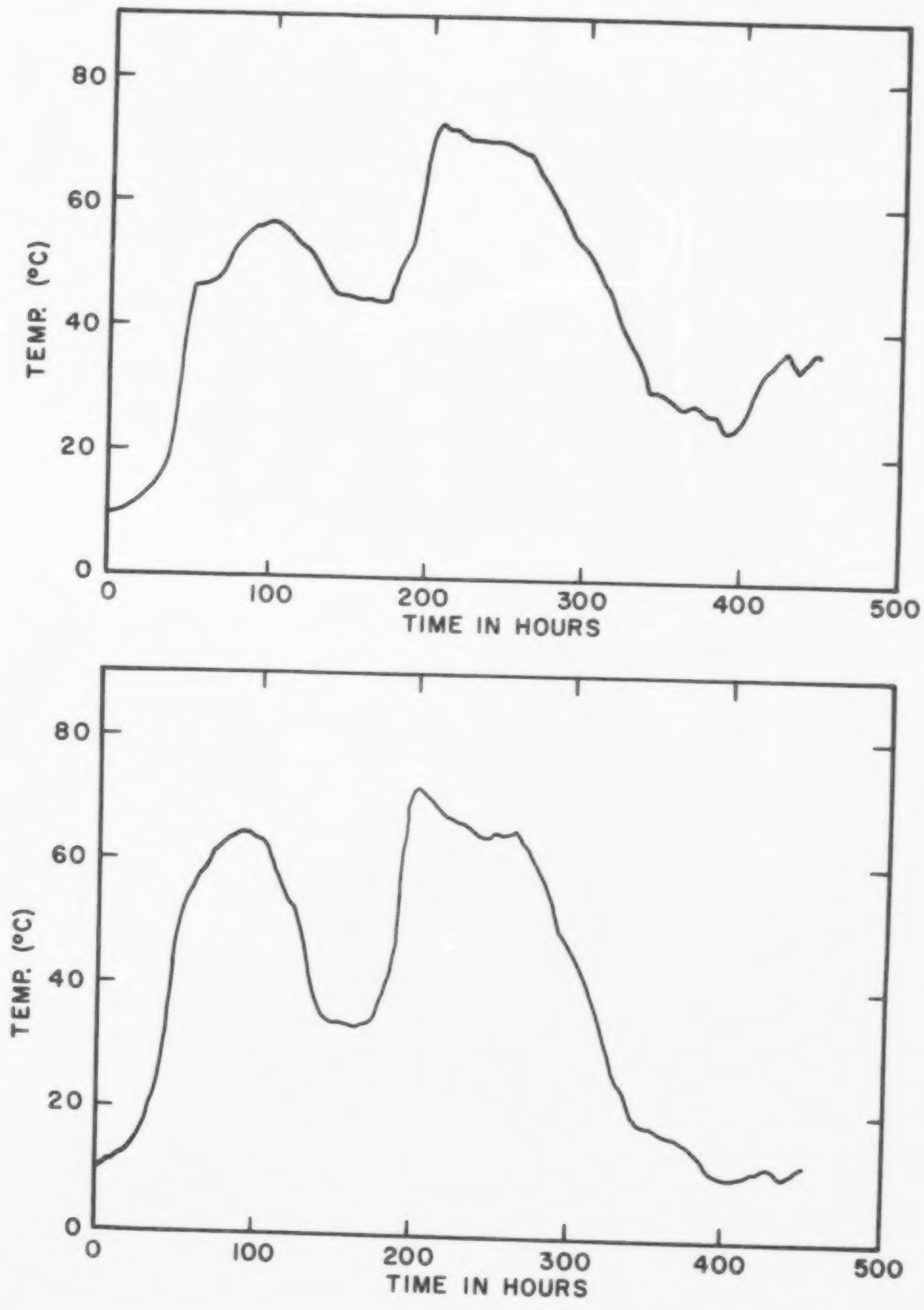
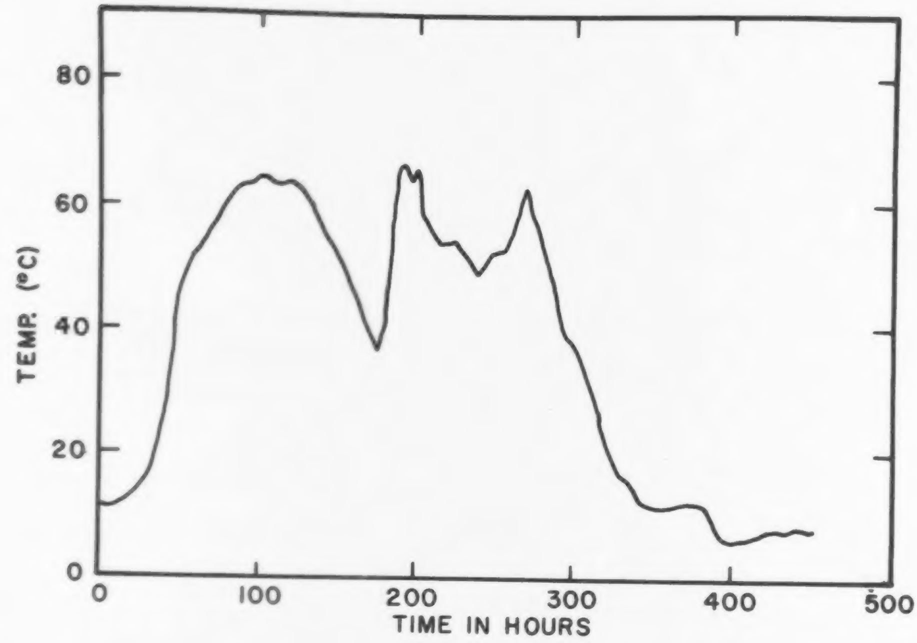


Figure 180. Pile 13, temperature at position 5 (upper plot) and position 6 (lower plot).



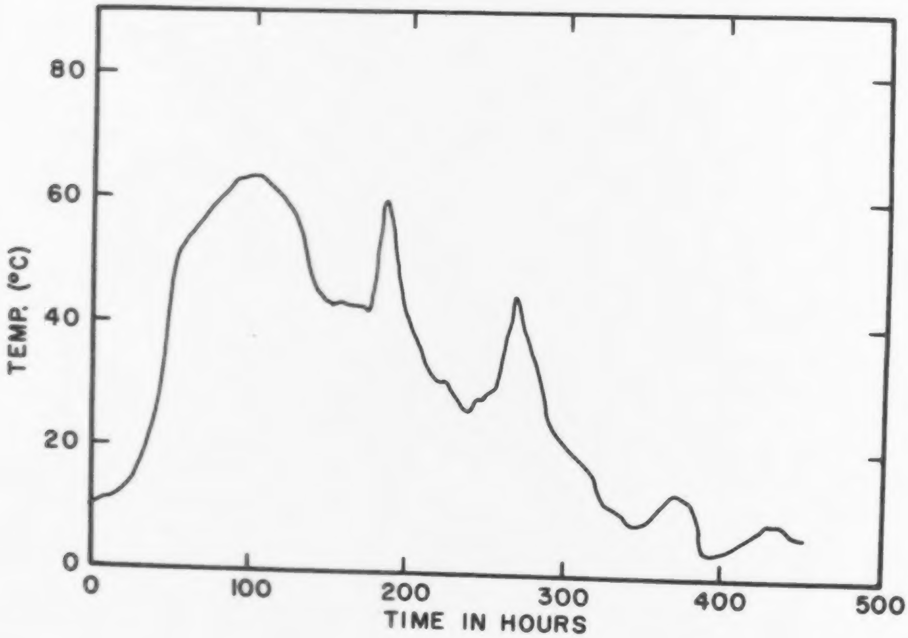


Figure 181. Pile 13, temperature at position 7 (upper plot) and position 8 (lower plot).

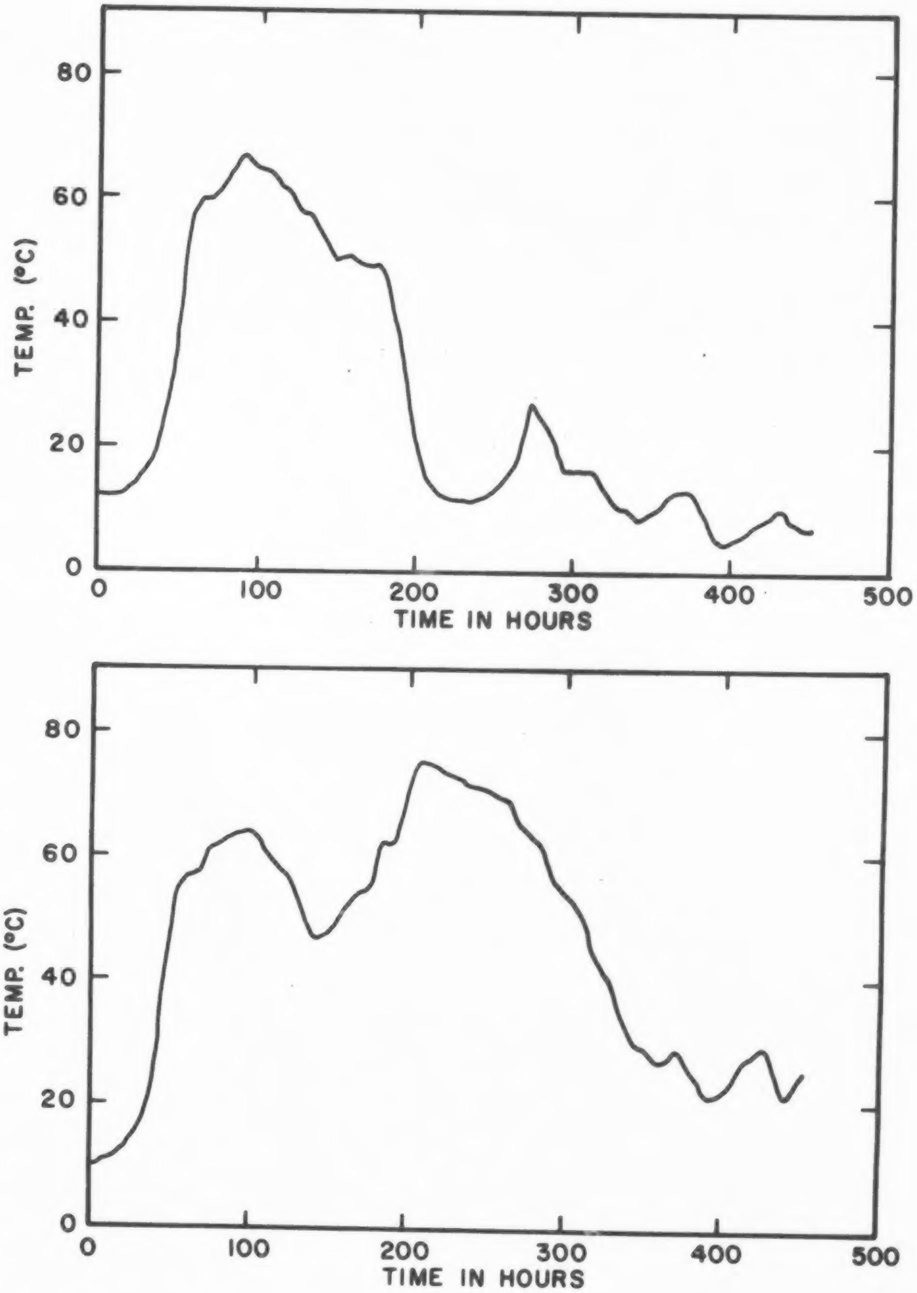


Figure 182. Pile 13, temperature at position 9 (upper plot) and position 10 (lower plot).

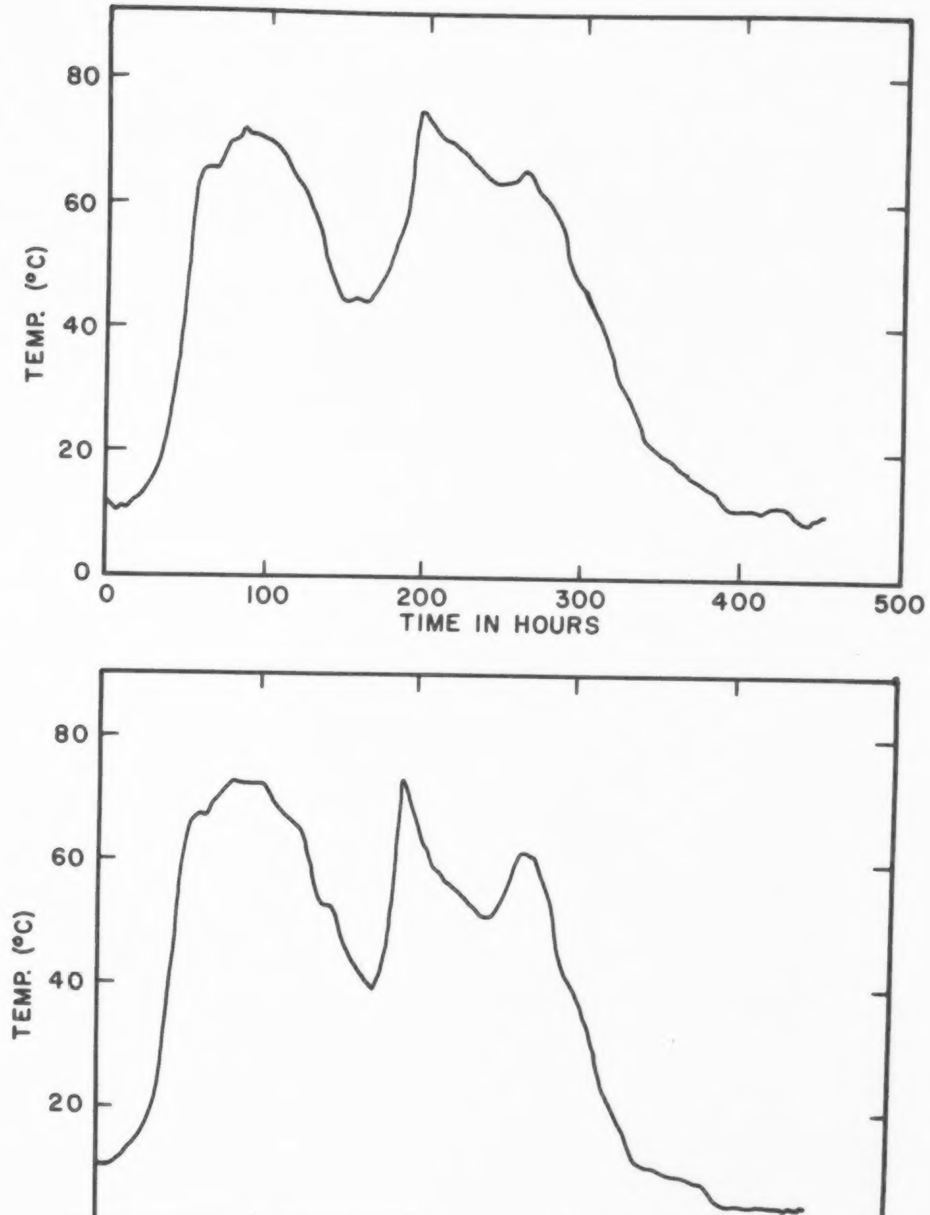


Figure 183. Pile 13, temperature at position 11 (upper plot) and position 12 (lower plot).

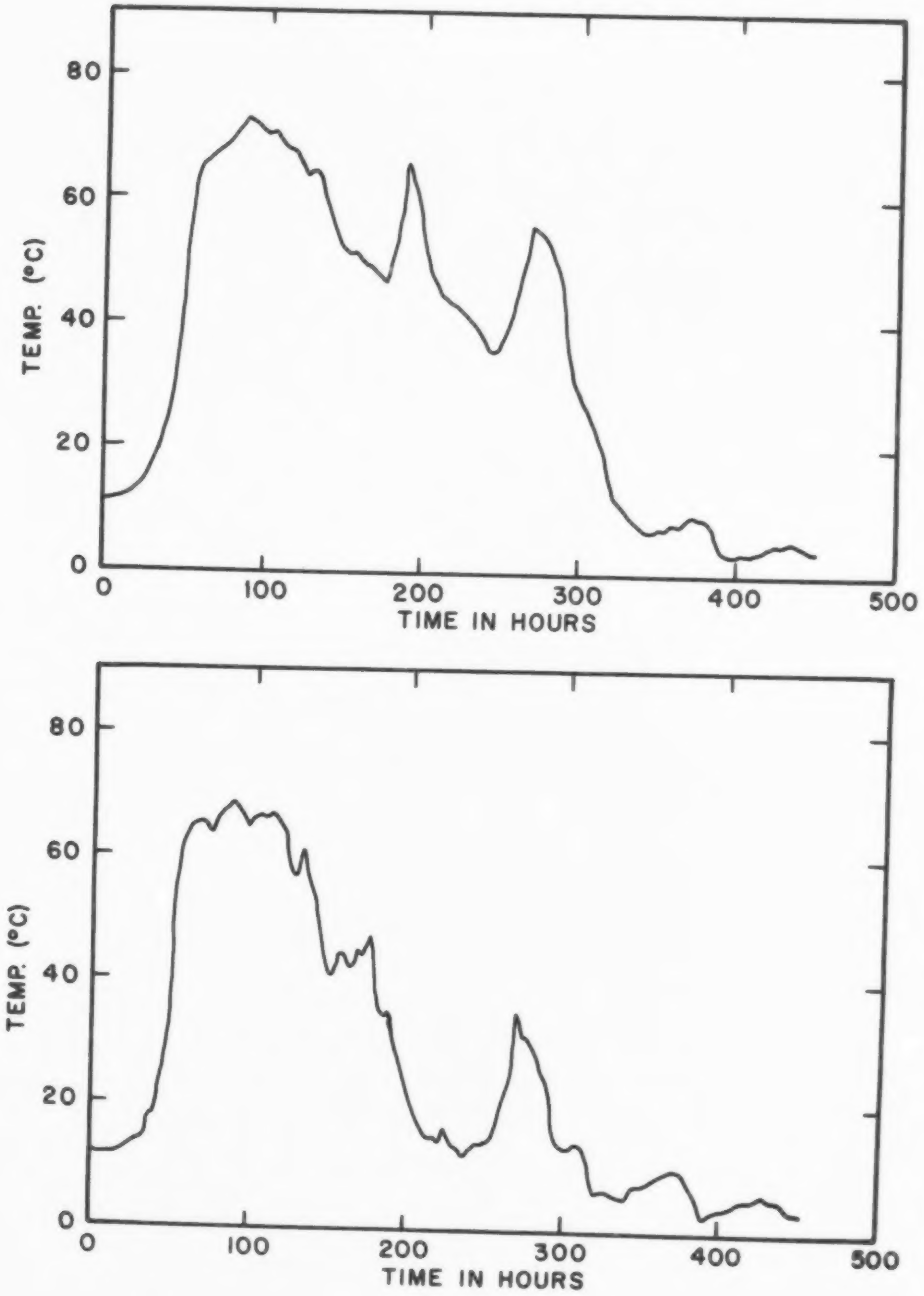


Figure 184. Pile 13, temperature at position 13 (upper plot) and position 14 (lower plot).

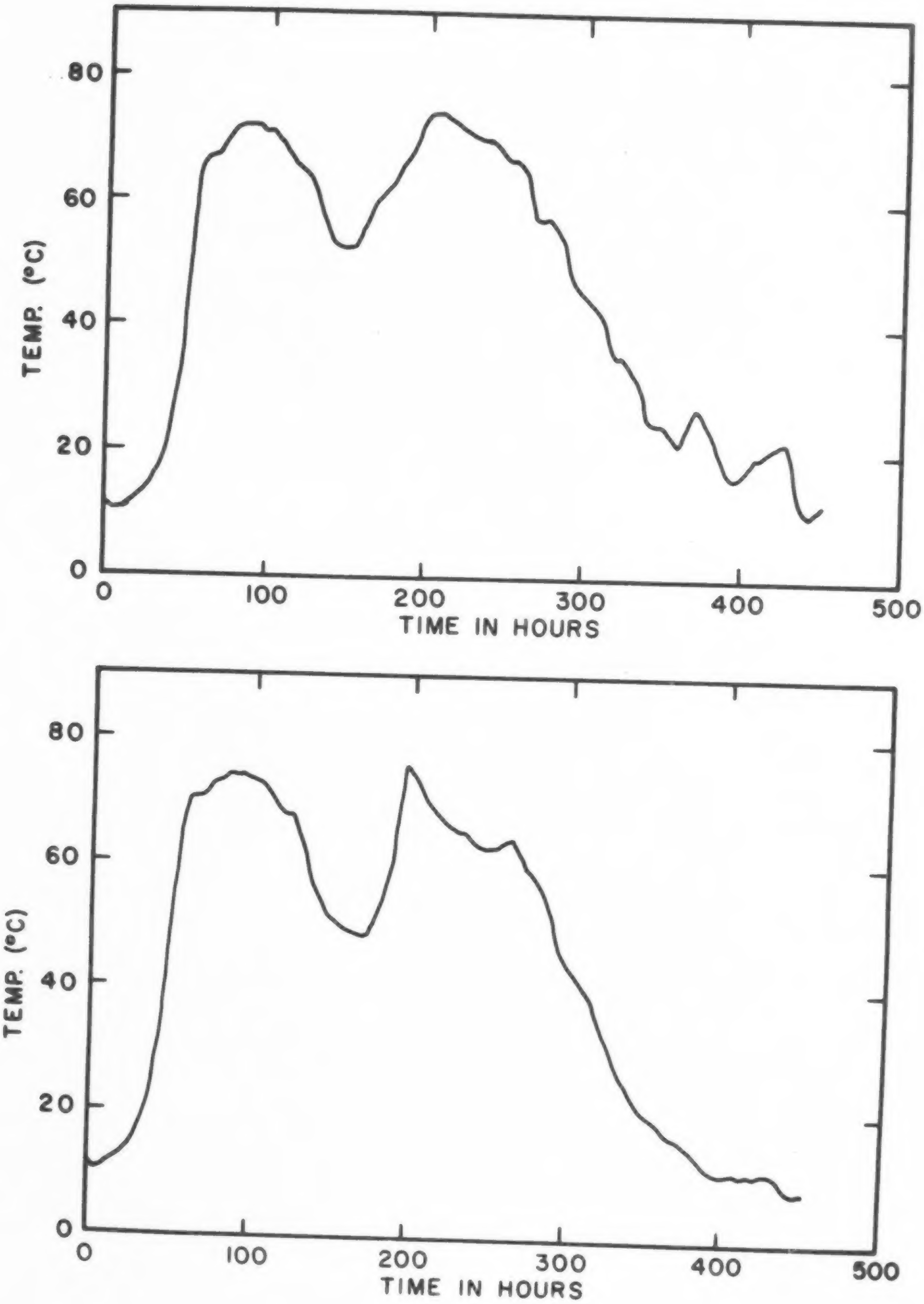


Figure 185. Pile 13, temperature at position 15 (upper plot) and position 16 (lower plot).

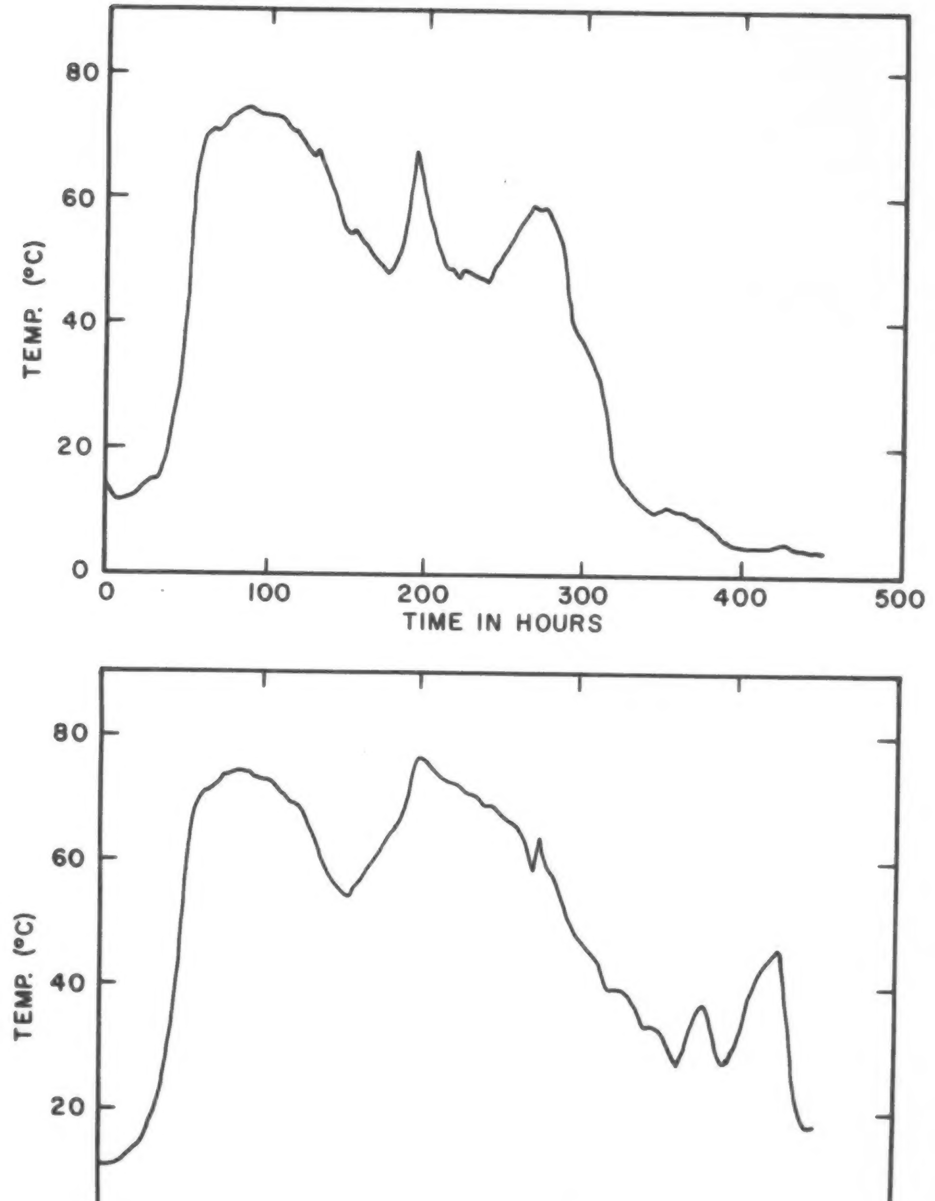


Figure 186. Pile 13, temperature at position 17 (upper plot) and position 18 (lower plot).

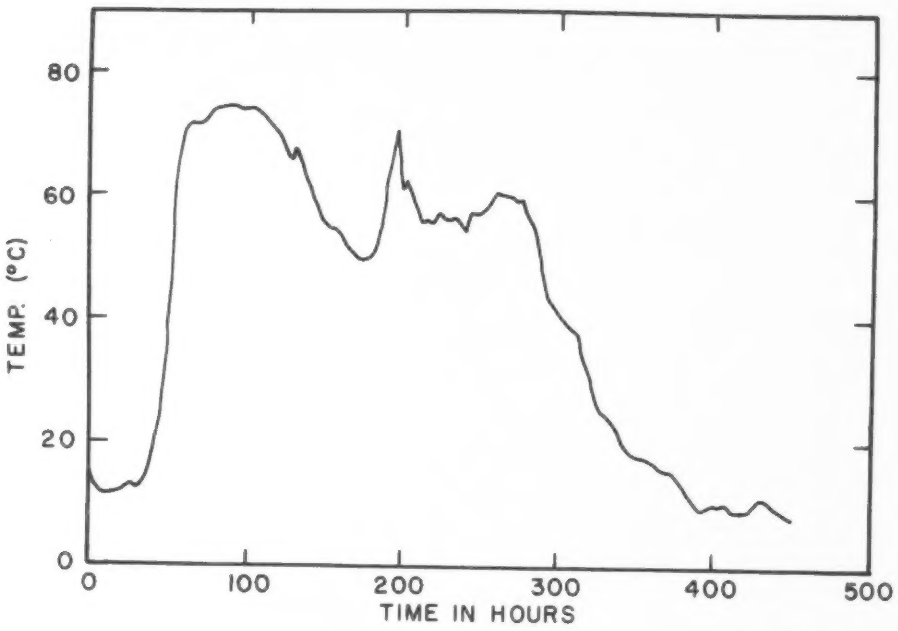


Figure 187. Pile 13, temperature at position 19.